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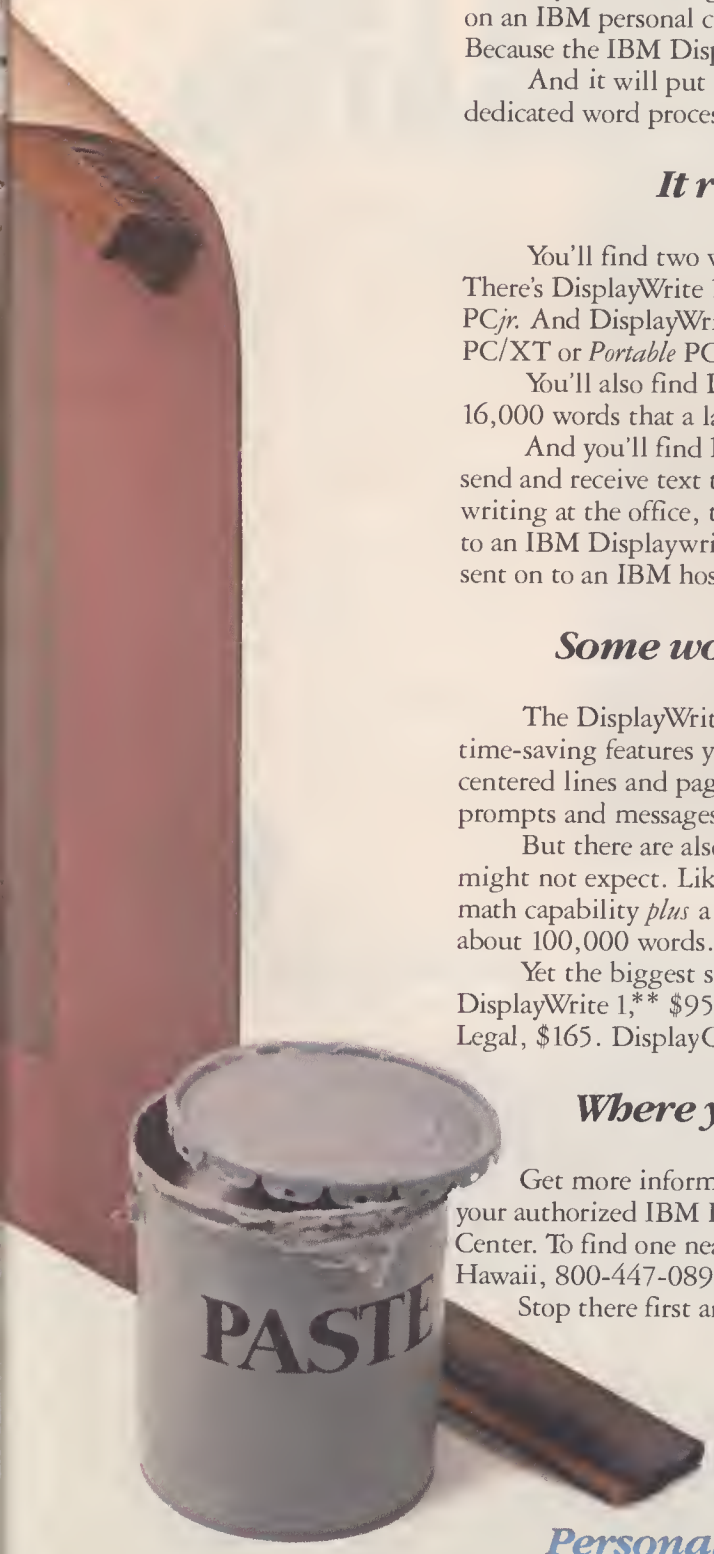
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This response is enhanced by a newly refined version of BMW's Digital Motor Electronics. A system so unerring it also manages the BMW engine that powers the current Formula One Grand Prix championship car.

In the BMW 325e the result is an aggressively smooth engine that delivers soul-stirring performance with a remarkable EPA-estimated 23 mpg, 36 highway.*

But as Road & Track states and BMW engineers concur, "the concept of performance encompasses a good deal more than the various aspects of acceleration."

It encompasses, for example, excellence in deceleration as well. For that reason the 325e is equipped with disc brakes on all four wheels. And they're vented in front to increase fade resistance.

The 325e has also been equipped with a newly engineered sport suspension that's fully independent with anti-roll bars at the front and rear for confidence-inspiring handling and a crisp yet supple ride.

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Inside the BMW 325e there are no sacrifices required in the name of high performance. Totally new BMW sport seats can be molded to your needs with a myriad of orthopedic adjustments.

While the instrument panel incorporates such informative BMW innovations as a Service Indicator that determines your individual driving style and recommends when routine services are due. And an onboard computer informs you of range on remaining fuel, average speed and outside temperature as well as other useful data.

The 325e exudes the same attentiveness to detail and quality that characterizes all BMWs and elicited this from Motor Trend: "doors close with a nice solid clunk, gear changes are crisp as cold celery and the steering as precise as a dial indicator."

In sum, it expands the prerequisites for all those cars seeking credibility as high-performance sports sedans. Every nuance of the 325e's performance has been heightened to elevate driving from a mere pastime into passion.

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JULY 1984

high Technology

VOL. 4, NO. 7

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COVER

Digitized image of a javelin thrower illustrates the application of computer technology to sports analysis. (Photo by David Madison; special effects by Mark Smith)

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ROBERT SPELLMAN

Don't bank too much on industrial policy

So many leaders have been calling for a national industrial policy that one is soon likely to emerge.

The rationale is straightforward. The U.S. has lost its leadership in many world markets while some nations, especially Japan, have had great success through support of targeted industries. In the U.S., government agencies set policies independently, possibly at cross-purposes, thus sometimes impeding rather than aiding new or foundering industries.

In theory, a national industrial policy would remedy this. But advocates differ significantly on how far this process should go. Some merely want government agencies to work toward the same goals. Others want a more active policy, including selection of "sunrise" and "sunset" industries for support or abandonment. An important question, though, is whether any national industrial policy will solve the underlying problem.

Consider, for example, an industry that has been nurtured by the U.S. government for a decade now: photovoltaics, or solar cells. The results could be instructive to those expecting government policy to solve problems in U.S. industry.

The photovoltaics effort is aimed at developing and bringing to market an alternative to electricity generated by fossil fuels. R&D progress has been remarkable across a broad front, from a wide range of materials and devices to working solar systems. No nation is even close to matching the U.S.'s breadth of achievement in this field.

Nevertheless, although it is still too early to tell, it appears that the Japanese may be making the investments and taking the early losses needed to gain dominance in the still-embryonic marketplace. Right now, thin films of amorphous silicon seem to have the greatest potential for mass-producing large, efficient solar panels at low cost. By targeting amorphous silicon, Japan has become a clear world leader in this sector. Manufacturers such as NEC, Toshiba, Hitachi, Fuji Electric, Sharp, Sanyo, and Kyocera, have taken on different R&D projects to develop products based on this technology.

Meanwhile, in the U.S., most significant vendors in the photovoltaics industry are wholly or partially owned by oil companies. They are concentrating on more costly crystalline silicon panels, primarily for large power company projects. RCA, whose photovoltaics group built the first amorphous silicon cell with over 10% efficiency, recently sold its developments to Solarex, which is backed by an oil company. Chronar, a small New Jersey company, and Sovonics, a joint venture of Energy Conversion Devices and Sohio, are entering the amorphous silicon thin-film panel market, but it is unclear how they will fare against much broader-based Japanese competition.

If U.S. businesses and investors are unwilling to take risks and pioneer new technologies, can any set of favorable government policies provide world leadership? No matter what industrial policy the nation develops, it's still up to a few visionary business leaders, with a feel for future markets and technology's potential, to make the U.S. a leader . . . or a follower.

Robert Haavind

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LETTERS

Reforming defense spending

In the Opinion "Where defense can be cut back" (Feb. 1984., p. 2), you called for reform in defense procurement. The panel of independent business executives you recommended exists in the President's Private Sector Survey on Cost Control, also known as the Grace Commission. I am proud to have served on one of its task forces, where I worked specifically on procurement practices for one of the armed services.

Operating from March 1982 until January 1984, the Grace Commission enlisted the volunteer services of over 2000 business men and women to review how the federal government was managed; over 40 task forces, run by chief and senior operating officers from the nation's best-known corporations, had direct access to the operations of the agencies they evaluated. For the government to duplicate that work would take at least 2 years and cost $75 million.

The reports of the task forces and of the full commission have already been delivered to the President, the Congress, and the Defense Dept. Task force reports found that the government could make three-year savings in the Defense Dept. and Armed Services (excluding pension reform) of over $64 billion. Those savings would come from such measures as:

- competitive purchase of commonly used parts and equipment—$7.3 billion over three years;
- improvements in DOD inventory management—$6 billion over three years; and
- closing unwanted military installations (in the face of congressional resistance)—more than $3 billion over three years.

John J. McGonagle, Jr., VP
The Helicon Group
Jamison, Penn.

Training managers

Yoshi Tsurumi's perceptive article has correctly identified the leading cause of the U.S.'s economic malaise ("Too many U.S. managers are technologically illiterate," April 1984, p. 14). However, the problem goes beyond technological incompetence. I am afraid we have institutionalized laziness in U.S. business management.

That is not to say that management does not work hard, but that it works hard at too many of the wrong things. Managers have recently placed more value on skills related to disposing of income, and less value on skills that produce income. Meanwhile, countries that have continued to produce wealth—notably Japan—have gained an advantage.

Happily, U.S. business is reemphasizing production. But leadership is not coming from academia. We are learning our lessons on the shop floors and in the design labs. Companies run by this new generation of business leaders will crowd out many of their MBA-guided counterparts.

Kevin A. Hoolehan
Reuben H. Donnelley
Terre Haute, Ind.

Tsurumi's article is a lucid, accurate, and truthful assessment of today's reality. The greatest technological danger to this country is not that the toxic byproducts of some new money-saving process will cause millions of cancer cases, but that the technologically inept and untrained corporate leaders will misuse what they don't understand. By concentrating on profits and failing to recognize the impact of their actions and their social responsibility, they are guaranteeing more problems tomorrow.

Ken Nazimek
Clifton, N.J.

There is a way to break the stranglehold of the academic-financial-legal complex on corporate officers. Truly crucial promotions are not those to the officer level but those to the pool of senior managers from which officers are selected. Promotions *from* this pool are assured some external consideration by virtue of the influence that boards of directors exercise over officer selections; yet promotions *to* this pool are controlled largely by incumbent officers. Thus the complex perpetuates itself. A partial solution is for concerned stockholders and boards of directors to reexamine and, perhaps, revise the criteria for promotion to senior management.

Frederick W. Nickols, Chief
Organizational Systems Technology
Nickols & Co.
Gaithersburg, Md.

I agree completely that better managers know their companies—and their facts. Yet Tsurumi is himself wrong when he states that U.S. Steel purchased Mobil Oil instead of modernizing steel facilities and keeping steel workers employed. One could argue about much of this sentence; but, in fact, U.S. Steel bought Marathon Oil, not Mobil.

J. B. Merrell, General Manager
Public Relations, Mobil Oil
New York, N.Y.

Error-correcting codes

"Quick fixes with error-correcting codes" (Jan. 1984, p. 18) is a well-written piece that provides the nonspecialist with much insight into a complex field. I do, however, have one objection to the last paragraph. It implies that interleaving is a powerful mitigation technique for burst errors only for block codes. This is far from the case. One of the more popular interleavers, called periodic or convolutional, was proposed in a paper by John Ramsey specifically for use with convolutional codes. Numerous convolutional decoders now in the field use this interleaver.

Andrew J. Viterbi, President
M/A-COM Linkabit
San Diego, Cal.

Editor's note: Andrew Viterbi recently received the 1984 Alexander Graham Bell Medal from the Institute of Electrical and Electronic Engineers "for fundamental contributions to telecommunications theory and practice and for leadership in teaching."

On the level

In "Superfighters" (April 1984, p. 36) you present an adept discussion of technical aspects of advanced fighters, but a common misconception needs to be corrected.

Conventional planes *can* change direction as well as rise or descend without changing attitude or pitch. I fly a Junkers Ju-52/3m (below) and have full ascent/descent control in level attitude via use of thrust, power, camber, and combinations of these. Other combinations allow turning without changing attitude. Of course, I may not be able to do these maneuvers as swiftly as a jet fighter, but I can do them.

Martin Caidin
Gainesville, Fla.

Editor's note: While it is technically true that conventional aircraft can do these maneuvers, they must sacrifice speed and stability to do so. For superfighters to accomplish these feats at supersonic speeds has required radically new developments in aerodynamic design.





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The moment of discovery is near.

Your fellow researchers are drawing on every shred of theory they've ever learned. And every scientist who ever inspired them.

Your research breakthroughs will change the way people understand the world. Your product breakthroughs will change their lives. But to get there, you've all had to discover resources you didn't even know you had.

In Pennsylvania, we're working hard to help companies like yours accelerate these kinds of breakthroughs.

We're creating a research and development environment unique in the nation: a partnership in which universities, businesses and state government join forces to help companies and small businesses create the technologies of the future.

And this partnership is working. As well as attracting attention. Pennsylvania was recently named #1 in state support of small business by *Inc.* magazine. And companies in fields ranging from biotechnology and biomedicine to robotics and CAD/CAM are already thriving here.

As you read this, more than 150,000 Pennsylvania scientists and engineers are at work on nearly every facet of advanced technology. These scientists and engineers represent the second largest concentration of such professionals in the East. What's more, four of the top 50 research universities in the nation are here—more than in any other Eastern state.

But a program called the Ben Franklin Partnership is what puts Pennsylvania at the forefront of technological development.

The Ben Franklin Partnership combines the talents and resources of Pennsylvania's universities, businesses and state government to accelerate the development and marketing of new technology. The Ben Franklin Partnership provides matching funds for applied research through its four advanced technology centers. It helps create programs for specialized work force training, and distributes seed grants to help small businesses grow.

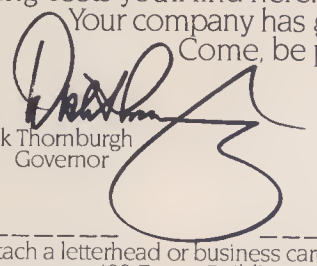
The Ben Franklin Partnership has developed an inventory of the research activity at Pennsylvania's universities and industries, and channels this information to private enterprise. And it can even provide incubator space for newly emerging companies.

Yet, as thorough as this partnership is, it lacks one essential element.

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UPDATE





Last Starfighter features advanced graphics

Strikingly realistic images of futuristic spacecraft flying through space, exploring a planet, and battling inside a hollow asteroid were created by a Cray X-MP supercomputer for the science-fiction film *The Last Starfighter*, released last month by Lorimar/Universal (HIGH TECHNOLOGY, June 1984, p. 40). Digital Productions (Los Angeles) generated the special-effects sequences at a resolution of 5120 × 4096 pixels. Each frame took the Cray about a minute to compute and was then transferred to 35-millimeter film via a digital film printer. Twenty-four frames had to be generated for each second of film time.

The frame at top right shows a futuristic spaceship called a gunstar moving through the clouds of the planet Rylos. The 3-D spaceship, consisting of a fine meshwork of about 300,000 polygons, was hand-digitized from a detailed set of blueprints. Special algorithms were then used to render the color and reflective properties of metal and glass surfaces, and to add streaks of carbon for improved realism. "As the gunstar goes through the movie, it accumulates layers of dirt with each battle," says Jim Rygiel, technical director at Digital Productions. The image at top left shows a "star car" taking off from earth. The cloud pattern was painted by a staff artist, scanned through a digital film printer, and mapped around a sphere.

Thin films keep electronics dry

A tiny pump with no moving parts, containing a water-absorbing plastic, can assure the dryness of sealed electronic components. A 1-ounce "microdryer" screwed into the electronics' casing absorbs moisture from aging plastics as effectively as a pound of silica gel, yet never becomes saturated. It can withstand temperatures from −50° to 110° C and seems to last indefinitely.

The heart of the microdryer is a thin film of DuPont plastic called Nafion, a Teflon with water-absorbing sulfonic acid sidechains. This film conducts a small current that dissociates absorbed water into hydrogen and oxygen.

The Nafion is sandwiched between porous nickel discs. A fluorosilicon film between the Nafion and the outside disc keeps water from diffusing inward but allows oxygen and hydrogen to escape. To prevent the gases from diffusing back toward the electronics, the inner face of the inside disc is coated with palladium, which catalytically recombines the gases into water. "This feedback loop makes the microdryer a chemical diode," explains Tomas Hirshfeld, a chemist at Lawrence Livermore Labs (Livermore, Cal.) who developed the pump.

Hirshfeld says that a 1/2-inch-diameter, 3/8-inch-long microdryer using 2 milliamps can pump up to 8 oz. of water a year.

Ceramic process saves time and energy

A new ceramic manufacturing process that promises to raise production rates and trim energy use has been developed at Battelle Memorial Institute (Columbus, Ohio). The technique, known as hot extrusion, could be used to make parts such as heat exchangers, batteries, combustors, and beds for industrial catalysts.

Ceramic powders mixed with plastic binders—typically polycarbosilanes, polycarbosilazanes, or polysiloxanes—are forced through a die under heat and pressure. The extruded shapes are heated further to decompose the binders, driving off the volatile constituents and leaving behind residues such as silicon, carbon, oxygen, and nitrogen that become part of the ceramic formula. The objects are then sintered (fired).

Hot extrusion has several advantages over conventional ceramic techniques. The particles left behind when the binder is decomposed have "active" (uncoated) surfaces that sinter at lower temperatures than the coated particles that sometimes result from other methods. And in heat extrusion there is no need for costly, time-consuming heat evaporation of water, as required by cold extrusion, in which ceramic powders are mixed with water and extruded at room temperature. Moreover, because the plastics contain inorganic materials that become part of the ceramic, it is not necessary to drive off all of the binder, as in injection molding.

Battelle researchers are studying how the binder and powder formulations can be tailored to extrude at optimal temperatures, since extrusion temperature strongly influences ceramics' physical properties.

Monoclonals track asthma drug

Although therapies based on monoclonal antibodies (MAbs) are still under study, several MAb diagnostic tests are now reaching the market. (MAbs are artificial proteins with natural antibodies' ability to recognize only specific molecules.) One of the most recent, developed by Du Pont (Wilmington, Del.), is an assay for the drug theophylline, which is used in treating chronic and acute asthma. Precise measurement of the amount of theophylline in the bloodstream ensures safe, effective treatment.

Theophylline relaxes the smooth muscles of the bronchi, the large branches of the trachea in the lung. However, it has a very narrow "therapeutic window"—the dosage below which it is ineffective but above which it produces serious side effects, such as nervous system and heart disorders. Accurate measurement has been hampered by the drug's similarity to caffeine; conventional blood tests are often distorted by coffee, soft drinks, and other caffeine-containing substances.

The new test (called PETINIA, for *p*article *e*nhanced *t*urbidimetric *in*hibition *i*mmuno*a*ssay) mixes the patient's blood sample with a proprietary reagent—latex particles chemically bound to MAbs that in turn bind exclusively to theophylline. The sample's resultant turbidity is measured on a standard spectrophotometer and is directly proportional to the amount of the drug.

Sunlight pumps gas laser

NASA researchers investigating space-based power systems have developed a gas laser that converts sunlight directly to laser output. By using a photoreactive gas as a lasant instead of pumping a CO_2 laser with energy collected by photovoltaic cells, the researchers hope to develop an orbiting laser-based power station that's simple, lightweight, and compact—thus reliable and cheap to launch. The sunlight-pumped laser would beam power in the form of laser light to nearby satellites and orbiting experiments.

The experimental laser developed by Ja H. Lee (Vanderbilt Univ., Nashville) and Willard Weaver (Langley Research Center, Hampton, Va.), uses perfluoropropyliodide gas (C_3F_7I) in a quartz tube as a lasant. Under artificial sunlight from a xenon-arc lamp, the laser produced 4 watts of power for 10 thousandths of a second in continuous operation. Peak power output was 10 watts in pulsed operation over 60 thousandths of a second.

C_3F_7I is not the perfect lasant, however. The iodine atoms dissociate during lasing, and about 5% of them form I_2 rather than recombine into the original lasant. The I_2 molecules compete with the lasing transition and put out the laser; they have to be swept out of the tube by flowing the gas. In space, that means irreplaceable lasant is lost. Futhermore, C_3F_7I absorbs light in the near ultraviolet, a weak part of the solar spectrum. Researchers are looking into improving the lasant by substituting a chlorine or bromine atom for one of the fluorines, and are testing other liquid and gaseous lasants.

Working solar-pumped laser power plants are ten or more years away. Lee and Weaver believe that a 300-meter diameter collector in near-earth orbit could provide 100 million watts of power to a solar-pumped laser, which would produce 100 kilowatts of laser output.

Standards sought for gasoline–alcohol blends

The National Conference on Weights and Measures is seeking uniform standards for use by state and local regulatory officials in testing gasoline and gasoline–alcohol blends.

Some standards already exist for testing gasoline, but these vary from state to state. Also, departments responsible for enforcing regulations governing retail quantity measurements are often not the departments that monitor gasoline quality. Moreover, the introduction of gasoline–alcohol blends in the marketplace "has caused new problems, not only for state officials but also for some car owners, retailers, and manufacturers," notes Sam Hindsman, chairman of the National Conference on Weights and Measures.

Alcohol, such as methanol or ethanol, used as an extender in gasoline can have a deleterious effect on rubber components. Also, moisture can cause gasoline–alcohol blends to separate, degrading vehicle performance. As a result, some manufacturers are limiting their new car warranties to exclude coverage of repairs if owners use fuel containing alcohol.

To hasten the development of new standards, and to produce uniform enforcement when standards are available, Hindsman has established a task force on motor fuels. The task force will support the efforts of the American Society for Testing and Materials in modifying the ASTM D-439 gasoline standard to include alcohol blends. The ASTM standard will serve as a national standard for adoption by the states.



New business in space

by Lester C. Krogh
Vice-President, Research and Development, 3M

Earlier this year, 3M and the National Aeronautics and Space Administration announced a joint venture to explore the commercial possibilities of space. NASA's role in long-term space research seems clear. But why 3M? Indeed, many have asked us why a rational, profit-seeking entity would want to gamble any of its resources on such a project.

One answer is that the potential of space fits 3M very well. We have long been a materials-processing company and are thus well aware that new materials lead to new products and new businesses. Moreover, our operations typically involve high-value/low-volume materials that are candidates for improvement through space-based process modifications.

3M has not yet sent any experiments into space, but we already know, for example, that some materials—such as water and oil—that will not mix on earth will do so in space. We know that low-gravity processing can eliminate many of the difficulties in growing crystals and can yield other unique results. We know that separation processes—as used for biologicals—that can be done on earth only with difficulty can be done in space quite readily and with greater purity.

The limited amount of materials processing that has been done in space has already revealed a number of opportunities. And these have whetted our appetites to know what else space science can teach us. We want to know if wholly new materials can be made in space. And we wonder if the extraterrestrial environment can help us develop products so advanced that they establish new definitions of "state of the art" in their fields.

But what we expect to gain from space, most of all, is learning. We want to find out where our agreement with NASA—to work together on long-term research in chemistry and materials processing in space—can take us. This makes the project extraordinarily exciting and represents its greatest challenge.

A venture of this sort entails risks, even for a major corporation. Substantial expenses will be incurred long before commercial applications—and revenues—begin to balance the picture. Our most optimistic projections of new products from our space research envision sales beginning no sooner than five years hence. In all likelihood, the leadtimes will be 10 to 20 years. But there is also a risk of *not* investing: A wait-and-see posture could endanger a company's competitive edge considerably more, in the long run, than its attempt to move out ahead.

Space science is a field in which we especially need to think globally. If U.S. space technology is not aggressively developed for its industrial applications, we may soon have competition from less timid nations.

The Japanese, for example, have built their own space center and are working on a three-stage rocket. The European Space Agency, led by France, has been successfully flying its Ariane expendable launch vehicle. West Germany has had its own lab in space. In duration, the manned space excursions of the Soviet Union are well ahead of ours.

The greatest risk, in our view, would be a lack of timely progress on the learning curve for space, where there is so much yet to be discovered. As the practical dimensions of space commercialization begin to emerge—and we are certain they will—we want to have as much intellectual momentum going for us as we can.

Space has been called industry's largest vacuum chamber and clean room. There is truth to both claims, although the part of space now being considered is not a perfect vacuum and is not entirely clean. But it is weightlessness in space that offers the greatest possibilities for industrial applications. For example, we may be able to develop containerless processing and new techniques for mixing liquids without convection.

Space is also vibration-free and completely quiet. These characteristics have not attracted the same attention as microgravity and vacuum, but they could be enormously beneficial to any process sensitive to background noise or vibration.

Until now, space research has emphasized exploration. But the work of NASA and the aerospace industry has convinced us that space science can now begin to emphasize utilization. And costs are moving within reach of companies that maintain basic research programs.

We all have a lot to learn. Even more, we may have a lot to forget. From elementary school on, we have been taught the limitations imposed on natural phenomena by the earth's atmosphere and gravity. These constraints might not deter us much longer, and we might have whole new sets of circumstances for our technical people to consider. We can then begin to integrate what we learn to do in space with the things we can already do on the ground.

As one 3M scientist recently put it: "I feel like a kid at Christmas, contemplating experiments I would not have dreamed possible a year ago."

We do not know what new ideas, new processes, and new priorities may arise. But we do know that the potential for expanding science and technology in space is limited only by our imaginations. □

The Robot Abstraction



The Robot Abstraction

Until now, matching robots to specific industrial tasks has been done by trial and error, requiring the creation of expensive prototypes. Recent advances at the General Motors Research Laboratories have produced a computer system that can be used not only to select the right robot, but also to program it to perform the task in the most efficient way.

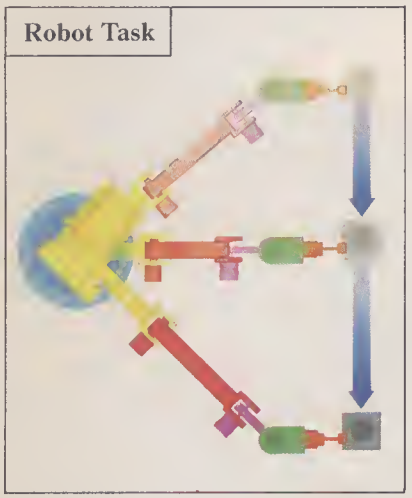


Figure 1: Two-dimensional overhead view of a robot task—the straight path trajectory of a solid.

Figure 2: Three-dimensional illustration of the robot work cell layout, showing reach capability for the task in Figure 1. Areas of color show total reach as well as the joint limits stored in the robot model.



THE DECISION to use robots to automate a manufacturing facility introduces the need for more decisions. There are several dozen kinds of robots, each with different capabilities. Thus far, choosing the right robot for a given set of tasks has been largely a manual process, involving great expenditures of time and money. By combining previously separate disciplines in a single computer system, two General Motors researchers have made the introduction of robots to the factory floor a more rational, less costly undertaking.

RoboTeach is the first computer system which integrates robotics, solid modeling, and simulation. It was designed and developed by Dr. Robert Tilove and Mary Pickett, both members of the Computer Science Department.

The use of powerful programming languages for manipulating robots is a major new development in the discipline of robotics. The languages specify desired robot motions, but they have no way of describing the robot's environment. Hence, they cannot automatically take into account physical obstacles or anticipate collisions. With only robot programming languages at one's disposal, assuring proper interaction with the environment requires testing with actual robots and parts.

Solid modeling, on the other hand, provides geometrically complete representations of environmental components and their spatial relations. But solid modeling cannot represent processes, because it has no way of representing temporal relations. Traditional solid modeling deals only with static relationships. While robot programming is without physical context, solid modeling is nothing but physical context. Neither by itself is adequate.

Nor are they satisfactory together. Only by simulation of both the robot and its environment can the sequence of discrete steps in a robot task be converted into the continuous motion of a process. Also without simulation, there is no way to represent accurately the robotic process as it unfolds in its environment.

RoboTeach, by combining all three disciplines, provides computer representations of the environment, the robot, and the task. Consequently, it helps users reach high-

level decisions about the real world without the investment of time or money in actual robots, actual parts, or the factory setting.

One key RoboTeach abstraction is a mathematical robot model. Solid modeling techniques represent the geometric form of each link of the robot. Then constraints are imposed on the relative positions of mating links to produce a mathematical abstraction of a mechanical joint. By insisting that the joint constraints always be satisfied, RoboTeach insures that the abstract robot model corresponds to a physically realizable geometric configuration.

OTHER representational facilities in RoboTeach handle robot task definitions. The representation of any task can be matched with the representation of any robot. In this way, RoboTeach helps users to determine the optimal robot for the task. Once a robot has been selected, RoboTeach can be used to program the robot off-line.

Not only are robots proliferating, but the tasks assigned to them are becoming more complex, making the need for off-line programming more urgent. When there are only a half dozen robots in a factory, the prospect of reprogramming them all by conventional show-and-teach methods for every new task is not overwhelming. But when there are hundreds of robots, the value of being able to reprogram without interaction with each robot becomes more apparent. Without off-line programming, the savings which justified the initial robot investment may quickly vanish.

RoboTeach distinguishes between two kinds of off-line programming: at the task level (what to do) and at the robot level (how to do it). For example, in the creation of a mechanical assembly, task-level instructions would include what components to assemble, the alignment of the components for the assembly process, and criteria for verifying that the final assembly is correct. Typically, there is a one-to-many relationship between task-level instructions and robot-level instructions.

"RoboTeach is currently in use," says Robert Tilove, "to study robot reach capabilities and to simulate simple robot-level tasks."

"Future research," adds Mary Pickett, "will explore the possibility of using RoboTeach to approach problems from the more abstract task level, with the user defining the task at a high level and RoboTeach filling in the details."

General Motors

GM

MARK OF EXCELLENCE

THE PEOPLE BEHIND THE WORK



Dr. Robert Tilove and Mary Pickett are Staff Research Scientists in the Computer Science Department at the General Motors Research Laboratories.

Mary Pickett received her B.S. in mathematics from Iowa State University and her Master's in computer science from Purdue University. She was a member of the team that developed GMSOLID, an interactive geometric modeling system. Her research at GM has also included the design of real-time programming languages. She joined GM in 1971.

Robert Tilove received his undergraduate and graduate degrees in electrical engineering from the University of Rochester. His Ph.D. thesis concerned the design and analysis of geometric algorithms for solid modeling. His current research interests also include the application of geometric modeling to computer vision and robot control. He joined GM in 1981.

MICROBIAL SCAVENGERS HIT THE OIL FIELD

Bacteria may help recover billions of barrels of oil from worn-out wells

Ever since the Arab oil embargo of 1973, researchers have stepped up their efforts to get partially depleted wells to give up their last precious drops of oil. While slack petroleum prices have reduced much of the impetus of the research, one such scavenging method—microbial enhanced oil recovery (MEOR)—now seems ready to assume a broader practical role in U.S. oil fields. The technology has the potential to glean more oil at less cost than all other tertiary recovery methods—techniques such as chemical or steam flooding that are used after all the primary and secondary production methods are exhausted.

Before MEOR can become a large-scale operation, however, researchers must expand databases on both the technology and the target reservoirs, develop economical food supplies for the microbes, establish control methods, and weigh the relative advantages of naturally occurring versus genetically engineered organisms. Thanks to recent field tests in Oklahoma, under DOE sponsorship, some of those goals are now close to realization.

The prospective payoff is a big one: DOE estimates that 300 billion barrels of oil, including that in tar sands, is inaccessible in the U.S. with primary and secondary recovery methods. About 17% of those reserves—50 billion barrels—could be extracted with tertiary methods.

When a well is first drilled, underground water and gas pressure pushes oil droplets into a bank and toward production wells. This pressure declines with increasing production, and the oil flow eventually slows down. Flooding the reservoir with water, a common secondary technique, can rebuild pressure and boost production once more.

When pressure and production decline again, the oil field operator may consider tertiary methods. These efforts face significant obstacles, however. The oil's viscosity tends to keep it immobilized, for instance, and it adheres tightly to rock surfaces. The oil in the reservoir is in discrete droplets rather than a coherent bank capable of moving toward the wellhead.

To wash out that oil—some 40–70% of the oil originally present—operators can inject steam to boost pressure and push the droplets together into an oil bank. That's the most popular third-stage recovery method, and the most economical, in the U.S. Another option is injection of chemical surfactants and detergents to dislodge remaining oil from rocks and wash it away. These techniques, however, can be costly and tricky to apply.

Microbial systems could be applied to wider ranges of reservoir conditions and would probably be easier and less costly to use. For example, if the letters on this page were embedded oil droplets, they could be recovered by only a few thousand microbes—all of which would fit on a single period. The microorganisms would be injected into the well along with suitable nutritive media—a mixture of molasses and water, for example, with perhaps a few minerals and other nutrients.

When the well is sealed, the microbes use carbon in the molasses to supply the energy needed for metabolism. Metabolic reactions, in turn, generate products that alter reservoir conditions: gases such as carbon dioxide or methane that increase underground pressure, acids that erode rocks and increase their permeability, or polysaccharides and metabolites that act as surfactants and reduce interfacial tension. Some species produce solvents, such as alcohols and ketones, that thin the oil and enhance its flow properties; others create heavy polymers that either plug up the pores in the rocks or increase water flooding efficiency. Microbes are selected for the reactions needed. After a month or so, when external measuring devices indicate that desired conditions have been attained in the well—increased pressure, for example, or reduced oil viscosity—production can resume.

The process is actually more complex than it sounds. Reservoir characteristics must be determined in order to properly select microorganisms and nutritive media. Moreover, microbial behavior under specific reservoir conditions must be well understood.

Unfortunately, such databases are "totally inadequate," says William R.



Declining underground pressure slows oil production at conventional wells like this one. In some cases, microbes may get the oil flowing again.

PHILLIPS

by Donna B. Doucette

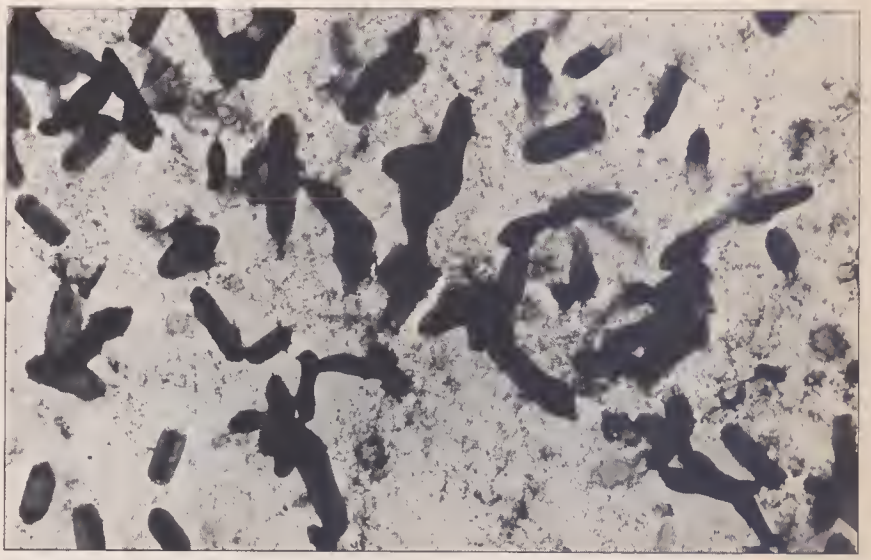
Finnerty, a microbiologist at the University of Georgia who conducts MEOR research for the Department of Energy. "The basic information is simply not available."

One reason is the secrecy surrounding private MEOR programs. How the systems work and why, the specific microbes used—even the overall field test results—are closely guarded corporate secrets. In 1982, for example, Mobil Research and Development published for the first time results of an MEOR test undertaken in 1954. Independent geologist Alvin C. Johnson developed one of the earliest MEOR systems, which he has applied at about 150 wells. But few of those tests have been publicly documented.

Overseas research presents U.S. scientists with another problem. Eastern European nations have apparently been applying MEOR techniques successfully for over 20 years. But data publication is spotty and often found only in obscure journals that await translation. An engineer at Phillips Petroleum (Bartlesville, Okla.), which held many of the early MEOR patents, says that only 50 of the more than 200 field tests conducted worldwide have been published in sufficient detail to aid other researchers.

In 1981, Erle Donaldson, then head of DOE's MEOR research at the Bartlesville Energy Technology Center, set out to get hard data with a federally financed field test. DOE provided support for a program—run by an Oklahoma State University microbiologist, the late Edward C. Grula—to select suitable species, test them in the lab, and determine proper nutrients. Grula was ready for a field test by the end of 1981, but he first had to convince an oil field operator to host the test.

One problem with MEOR is that microbes are anathema to most oil professionals, who spend much time, effort, and money to ensure that harmful bacteria—which corrode equipment and poison the recovered crude—do *not* enter a reservoir. They also must neutralize bacteria indigenous to the field. "They were spending millions of dollars to get rid of these bugs," Donaldson says, "and they would look at me and say, 'Are you crazy, trying to get us to put bugs *into* the wells?' I would explain that they were mixing up their bugs. These are different from the organisms that harm a reservoir."



Bacteria such as these Clostridia could aid drillers by forming gases that repressurize the reservoir, as well as chemicals that help the oil flow from underground banks to the well.

Oil recovery organisms include bacteria and some fungi, such as *Arthobacter*, *Bacillus*, *Clostridia*, *Candida*, *Enterobacter*, *Mycobacterium*, and *Pseudomonas*. With so many options, selecting the species that can best tolerate the conditions of a specific reservoir can be tricky. Temperature, salinity, pH, pressure, permeability, and porosity must all be analyzed. And because reservoirs are heterogeneous, what's suitable for one section may not be best for another.

Nutrients are another question. To grow, microbes need nitrogen, sulfur, magnesium, iron, and phosphate, although some species grow without one or more of these nutrients. In all cases, though, they need a carbonaceous energy source.

Some microbes, at least in the lab, can grow on the carbon in the oil itself. Generally, however, microbes must get energy from carbohydrates: beet or sorghum molasses in water, for example, or glucose and ammonium sulfate. Researchers must also consider the effects of these nutrients on bacteria already in the reservoir. Fortunately, the injected microbes would be better suited than the indigenous ones to exploit the food source.

Considering all those factors, Grula selected *Clostridia* for the DOE-sponsored field test. The microbes "will not form corrosive substances and will not plug up equipment," he explained. "They will simply disintegrate once we stop feeding them."

The DOE field test began in September 1983 in Oklahoma, at Sand Springs and Sapulpa. Results from the two wells are encouraging so far, according to Donaldson, now with the University of Oklahoma's petroleum engineering department. A full report on the project, presented at a recent conference, will be distributed later this year.

Meanwhile, the rest of the industry has not been standing still. Three years ago, Phillips teamed up on genetic research with the Salk Institute's Biotechnology Corp. (La Jolla, Cal.). Among the venture's goals is the commercialization of MEOR methods using genetically engineered microbes. Phillips sources say, however, that MEOR research is long-term and has been relegated to "back burner" status.

This year Petroleum Sciences (Houston), a leader in MEOR research, plans to sponsor 100 or more field tests now being designed by Alvin G. Swan, director of research at the Science Research Center of Hardin-Simmons

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University (Abilene). These tests will use only naturally occurring organisms. "First," says Swan, "it's devilishly difficult to get genetically engineered species approved; people are afraid of them. Second, it's hard to get genetically engineered organisms that are anaerobic"—i.e., microbes that can grow in the oxygen-poor environment of petroleum reservoirs.

Mobil Oil is also pursuing MEOR. In the 1954 test—Mobil's last documented work, according to U. of Oklahoma's Donaldson—*C. acetobutylicum* was injected into an oil field in Union County, Ark. Production at the site increased from one barrel per day to three, but the project was shut down after a year because of lower oil prices. Now Mobil has resumed MEOR testing, this time in south Louisiana. The company declines to provide details, however.

Tripled production is not unusual. MEOR sometimes yields dramatic results. At sites where independent geologist Johnson's process was applied, for example, increases as high as 250%—from 2 barrels a day to 7—were obtained. And reports from Eastern European nations cite production increases as high as 300%.

In contrast to such successes are reports of wells where production increased only temporarily or not at all. Many of those results were obtained in Eastern Europe, so full details are not available. The Johnson process reportedly attains a 50% success rate.

Other nations with an interest in MEOR include Australia, the Netherlands, China, Switzerland, and Israel (where microbes are used to clean oil tanks and produce fuels). British and Canadian researchers are also studying the process as a possible means to enhance recovery rates in the North Sea and Alberta.

Tapping left-behind oil with microbes, however, will remain an elusive goal until certain obstacles are overcome. For example, several industry sources note that recent oil prices have been too low to justify broad implementation. Moreover, most tests to date have been run at wells with average daily outputs of less than 10 barrels. "MEOR works fine for those applications," says J. Bennett Clark, senior research microbiologist at Phillips. "But oil companies are interested in reservoir-wide application, not just use in one well. That application is still a few years away." ☐

Donna B. Doucette is editor of Energy Research Reports *in Watertown, Mass.*

MILITARY rDNA RESEARCH STIRS DEBATE

Methods to foil biological warfare agents could lead to new weapons

The U.S. military's use of recombinant-DNA (rDNA) techniques is sparking controversy within the biotechnology community. Since 1980, the Dept. of Defense has initiated 61 projects involving the use of rDNA methods and monoclonal antibodies to produce vaccines against diseases that troops might encounter abroad and antidotes to biological warfare (BW) agents. Fifty-four of these projects are run by the Army, at a cost so far of $24.7 million, and seven by the Navy, at a cost of $1.4 million.

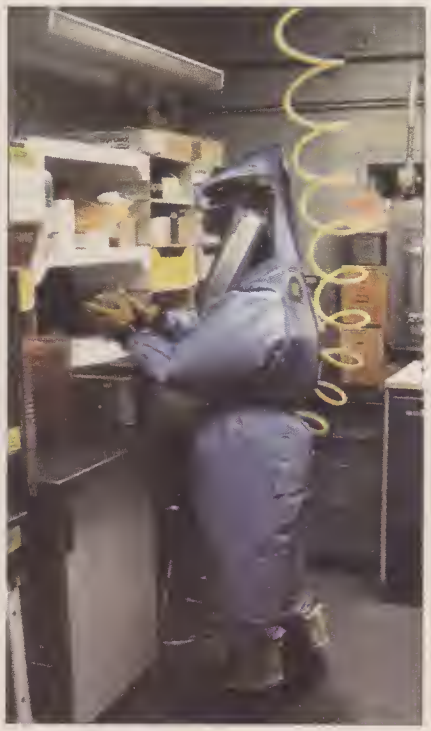
Although the development and stockpiling of BW agents is prohibited by the Biological and Toxin Weapons Convention of 1972, the treaty permits defensive research for "prophylactic, protective, or other peaceful purposes." The Army contends that the United States should maintain an active defense against potential BW agents. But critics worry that such research could lead to deadlier offensive weapons in the future.

In fiscal year 1984, the Dept. of Defense budgeted $5.4 million for Army and Navy infectious-disease research involving rDNA techniques and monoclonal antibodies; the request in the FY85 budget is for $18 million. About half the research takes place in Army and Navy laboratories, such as the U.S. Army Medical Research Institute for Infectious Diseases (USAMRIID) at Fort Detrick, Md. The remainder is contracted out to genetic engineering firms and university research groups.

The Army is currently funding the development of vaccines for a wide variety of diseases, including malaria and other parasitic infections, hepatitis, rickettsial diseases, four types of dengue fever, and diarrheas and dysenteries. Vaccines are also being developed to combat viral and bacterial diseases and toxins—such as anthrax, tularemia, Rift Valley fever, Lassa fever, botulinum toxin, and mycotoxins—that pose potential BW threats.

Many of these vaccines are being produced with rDNA techniques. The new technology involves isolating a segment of the microbial DNA that codes for a surface protein, or antigen, capable of inducing immunity. Copies of the antigen gene are inserted into common bacteria, which then churn out large amounts of the foreign protein. For example, the Army has hired Molecular Genetics (Minnetonka, Minn.), a genetic engineering firm, to develop a vaccine for the Rift Valley fever virus, which affects both animals and humans in northern Africa. Producing such a vaccine with conventional methods, such as by purifying antigens from large quantities of the virus, would be impractical and hazardous.

Col. David L. Huxsoll, commander of USAMRIID, believes it is important for the U.S. to maintain an active defensive posture against potential BW agents. "I would rather have some defense against these agents than none," he says. "The options available to an adversary who might be inclined to use them would be reduced." Huxsoll also points to the need to defend the U.S. civilian population against possible terrorist use of biological weapons.



Army scientist works in Infectious Disease Containment Lab at Fort Detrick.

KENNETH GARRETT

by Jonathan B. Tucker

But critics say it is impossible to distinguish between defensive and offensive research. They contend that by developing defenses against biological warfare agents, the Army is obtaining the technology to produce more lethal microbes in the future, should the Biological Weapons Convention ever be revoked. "Obviously, one wants to have vaccines against diseases that the military or other people might naturally encounter," says Robert L. Sinsheimer, a biophysicist and chancellor of the Univ. of California at Santa Cruz. "The point is that as you acquire the ability to do this by studying the genetics of a virus and isolating particular genes with recombinant-DNA techniques, you also acquire the ability to make new variants."

In principle, novel biological warfare agents could be engineered by modifying or recombining genetic factors to enhance the selectivity, lethality, or stability of known disease-causing microbes. Recombinant-DNA techniques could also be employed to produce large quantities of lethal toxins in bacteria under controlled laboratory conditions. Critics worry that such military uses of rDNA techniques could pass through loopholes in the Biological Weapons Convention. For example, the treaty defines a toxin as a poison produced by "living organisms," yet it is unclear whether this definition covers a modified toxin manufactured by a bacterium that would not ordinarily produce it.

The Army "is looking forward to the time when biological warfare agents might be developed and is taking whatever steps it legally can toward that development," contends David Dubnell, a staff scientist at the Public Health Research Institute (PHRI) in New York. But while Col. Huxsoll ad-

SCIENCE/SCOPE

NASA's Project Galileo may provide clues to the origins of the solar system when it explores the planet Jupiter later this decade. Project Galileo is scheduled to be launched from the space shuttle in May 1986 and arrive at the giant planet in August 1988. The mission consists of two spacecraft. One is an orbiter that will circle Jupiter for 20 months. The other is a Hughes Aircraft Company-built probe that will plunge into the planet's brightly colored clouds and relay data about the atmosphere. The probe is expected to operate for about 50 minutes before succumbing to temperatures of thousands of degrees, limited battery capacity, and pressures up to 10 times that of Earth's at sea level. Because some scientists believe that Jupiter's atmosphere is a sample of the original material from which stars are formed, the probe's findings will be closely studied.

Residents in central Indiana are the first in the U.S. to receive television programs in their homes broadcast directly from a satellite. Last November, United Satellite Communications Inc. began the first direct broadcasting satellite (DBS) transmissions to homes in 33 counties surrounding Indianapolis. Transmissions were relayed via Anik C2, designed and built by Hughes for Telesat of Canada. Homes receive the signals through antenna dishes that are less than three feet in diameter and sell for about $300. The more familiar satellite receiving dishes found in rural areas of the U.S. average four to five feet in diameter and sell for more than $2,000. Initial programming includes two satellite movie channels and the ESPN sports network.

A network of small "smart" radios will let U.S. troops and their commanders know where they and friendly forces are located at all times. With the Position Location Reporting System (PLRS), combat troops will no longer have to seek landmarks to pinpoint their location. PLRS automatically supplies position and navigation data in digital form through a computerized communications network that displays data on a small hand-held box. PLRS units can be mounted on vehicles, aircraft, and helicopters. All units serve as automatic relay stations, so that units far away from a master station can stay in touch regardless of terrain or weather. Hughes is producing PLRS for the U.S. Army and Marine Corps.

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mits that offensive applications are theoretically possible, he says that the Army is engaged in a purely defensive effort and has no intention of developing new BW agents. "We don't do that kind of thing," he insists.

Nevertheless, the recent controversy over "yellow rain" and other alleged violations of the Biological Weapons Convention, combined with the worsening of U.S.–Soviet relations, has raised fears of biological weapons rearmament. Indeed, the Pentagon's 1984 report on Soviet military power contends that the USSR has "at least seven biological warfare centers." The report also notes "an apparent effort on the part of the Soviets to transfer selected aspects of genetic engineering research" to these centers. Dubnell, Sinsheimer, and others are therefore advocating that the Biological Weapons Convention be supplemented with another treaty prohibiting rDNA research that could enable the construction of novel biological weapons—either organisms or toxins. The proposed treaty would include mechanisms for verification and enforcement.

Sinsheimer also recommends that defensive vaccine research be limited to civilian labs, such as those run by the Dept. of Health and Human Services (HHS), and that the results be made freely available to scientists of all nations. "To a large degree, it's a question of mind-set," Sinsheimer explains. "I think it would be much less likely for civilian researchers to start thinking of ways of making new biological weapons than for military people." Col. Huxsoll replies that while HHS addresses infectious-disease problems of general interest to the civilian community, the Dept. of Defense concerns itself with protecting the armed forces. "Since we are working with unique military problems," he says, "we feel that [this research] should stay within the Dept. of Defense."

Another focus of the Army's rDNA research program is the development of reliable antidotes to chemical nerve-gas weapons, on which effort the Army spent $100 million in FY84. The four nerve gases in current arsenals (GA, GB, GD, and VX) work by interfering with the action of the neurotransmitter acetylcholine at the junctions between nerves and muscles, causing convulsions, paralysis, respiratory failure, and death. The Army is attempting to develop prophylactic antidotes for protecting soldiers against nerve gas before they go into battle, as well as drugs for treating exposed individuals.

The Pentagon's 1984 report on Soviet military power notes "an apparent effort" by the USSR to use genetic engineering for biological warfare.

Such antidotes would not inactivate the toxic agents but would block their action until the body's enzymes could metabolize them.

Although the four nerve gases have similar chemical structures, they have different mechanisms of action. Most of these agents inhibit acetylcholinesterase, the enzyme that inactivates acetylcholine after it has triggered muscle contraction. But some also appear to attack the acetylcholine receptor, the ion channel associated with it, or both. "There are all kinds of permutations," says Col. Ed Houston, research area manager for the Army's medical/chemical defense project. "That's what we're trying to sort out now in our research."

Because it is impractical to purify large quantities of acetylcholinesterase with conventional techniques, the Army has awarded contracts worth over $1.3 million to research groups at the Universities of Arizona, Massachusetts, and California/San Francisco, the Invarest Corp. in Scotland, and the Weizmann Institute in Israel to clone the human gene for the enzyme. The idea is to insert copies of the gene into a simple organism such as the intestinal bacterium *E. coli*, which would manufacture large quantities of the protein. Army scientists could then use chemical analysis, x-ray crystallography, or computer modeling to determine precisely how nerve gas interacts with the enzyme, facilitating the design of chemical antidotes.

Harvard molecular biologist Jonathan Beckwith, a critic of the research, contends that the information derived from antidote studies could be used to design more effective nerve-gas weapons. But Col. Houston disagrees. "I have no activities going on that are involved at all in making a better agent, nor is it our intent to do that," he says, adding that an antidote to nerve gas would actually improve deterrence of chemical warfare.

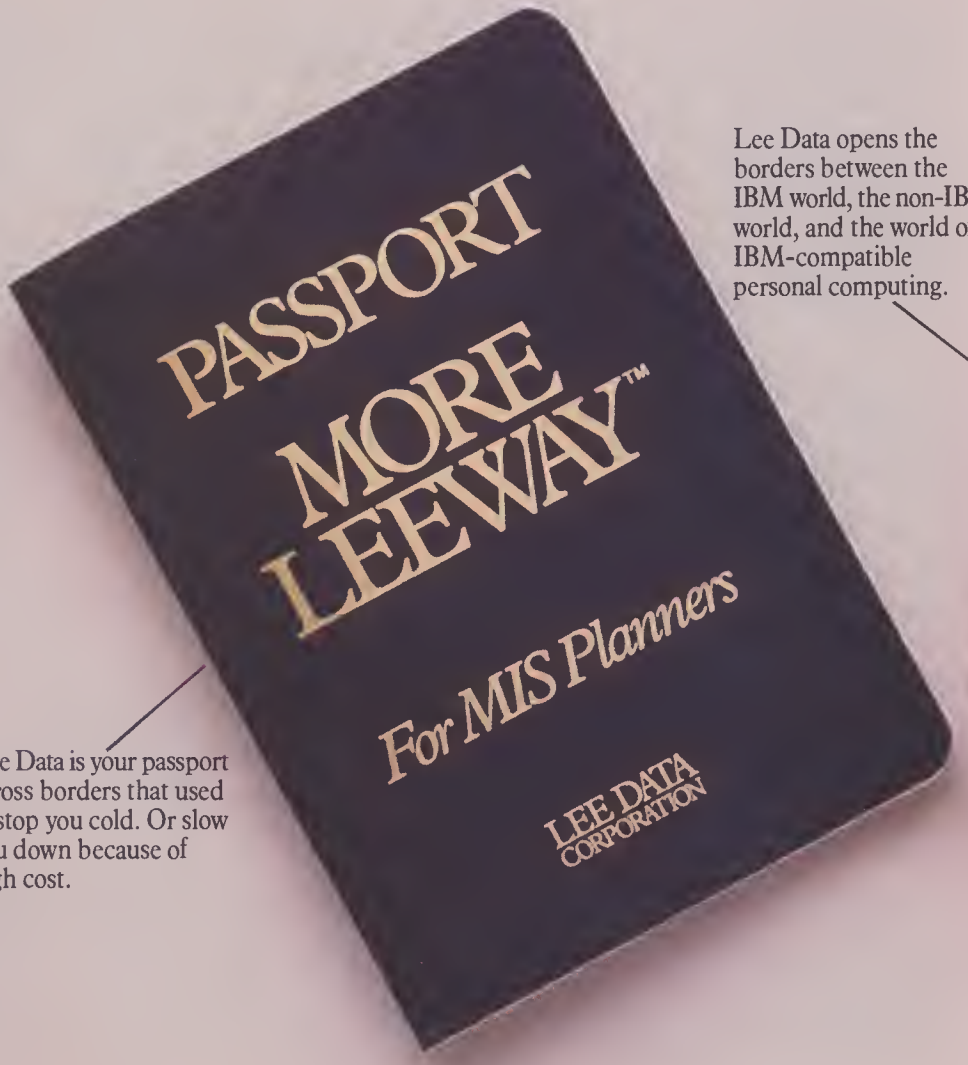
Some critics argue, however, that a reliable defense against nerve gas would destabilize deterrence by triggering an upward-spiraling arms race between defensive and ever more lethal offensive systems. Says PHRI's Dubnell, "I think history has shown that if you begin to develop defenses against weapons, in the long run it encourages the other side to develop weapons to overcome your defenses."

In a recent article in *GeneWatch*, a newsletter on the social implications of biotechnology, Susan Wright, a historian of science at the Univ. of Michigan (Ann Arbor), warns that rDNA technology is today where nuclear physics was in 1940:

> Although we have not yet invented novel biological weapons, it seems clear that we have the technical capability to do so. The critical question is whether we can learn from the experience of nuclear physics. The application of that field for weapons purposes, fueled by the logic of protection and counter-protection, has brought us to the brink of nuclear annihilation. Unless we renounce that logic, we run the risk of being swept into a new weapons race—this time based on biology. Efforts directed toward negotiation and the control of biological weapons are surely less risky than the alternative of not attempting to take this step. □

Jonathan B. Tucker is a senior editor of HIGH TECHNOLOGY.

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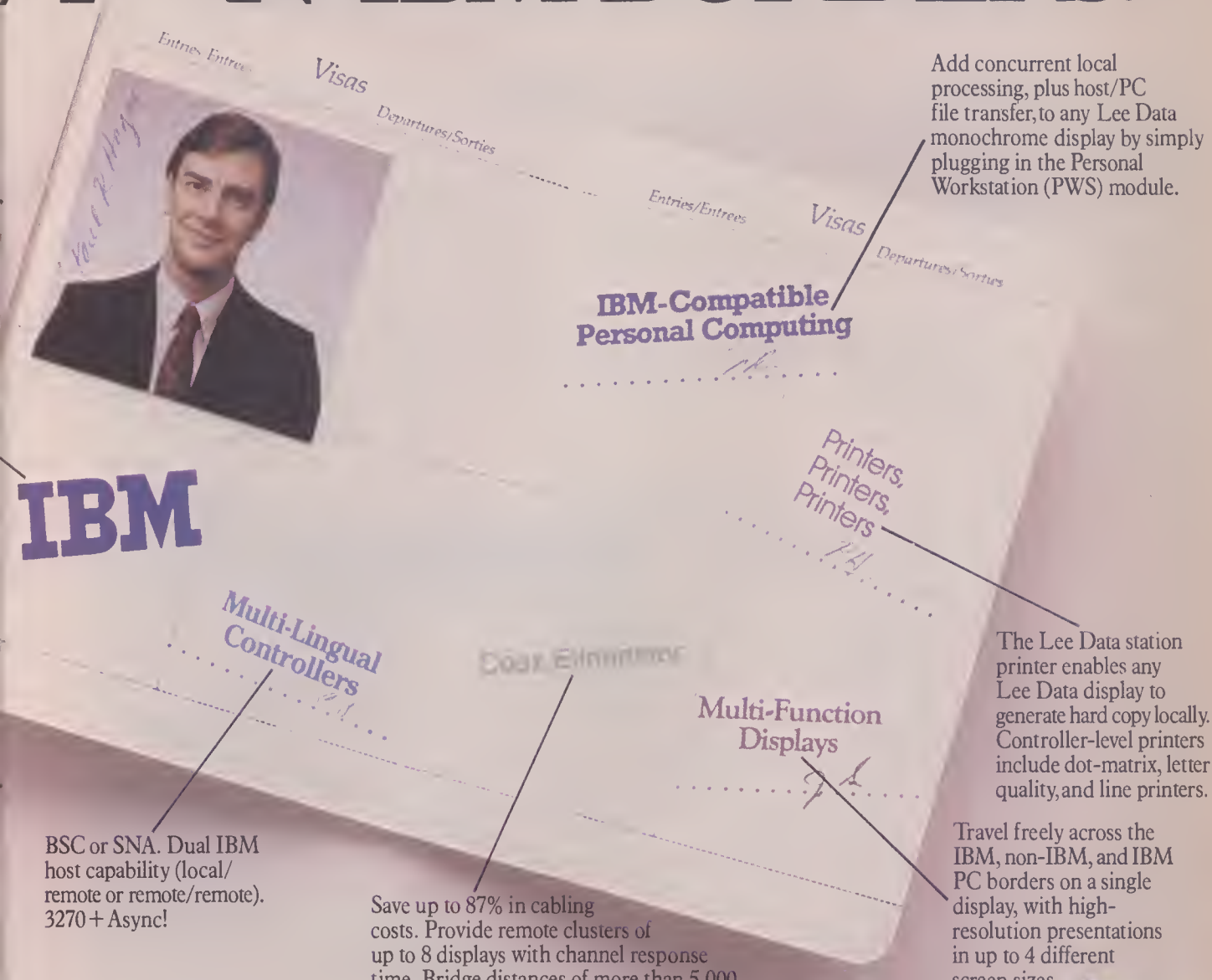
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DESKTOP PLOTTERS DRAW BUSINESS USERS

Smart devices merge electronic power with mechanical precision

Plotters that draw charts and graphs from digital data have been around nearly as long as computers. Used primarily in laboratories, the first plotters were mechanically precise but large and expensive. The early machines were also electronically "dumb," and depended entirely on commands from a host computer. This arrangement burdened the host—typically a large mainframe computer—and required sophisticated software, written by talented programmers.

Recently the growing popularity of business graphics software has stimulated a demand for plotters in the same way that ubiquitous word processing software spawned a market for letter-quality printers. This new demand for plotters has resulted in the production of small desktop machines that cost from $600 to $6000.

Most important, the new plotters have internal microprocessors and are intelligent enough to be run from small business computers operated by unsophisticated users. In fact, plotters are now smart enough to be considered computers themselves. "You could hook a full-scale keyboard and a monitor to them, and they could run as computers," says Richard Murray, cofounder and chief engineer of Enter Computer (San Diego), a manufacturer of small plotters.

Graphics-pen plotters create drawings just as a human artist might: by putting pen to paper. Since all lines, whether curved or straight, are a combination of movement in the X and Y directions, plotters can draw even complex graphics by properly coordinating pen and/or paper movement in these two directions. Plotters may either hold the paper fixed and move the pen along both coordinates or move the pen along one coordinate and the paper along the other.

Mechanically, pen plotters may be one of three types: flat-bed, drum, or a new style called a paper mover. All three have a horizontal carriage bar along which a pen shuttles. Flat-bed plotters hold the paper in place and move the entire carriage bar vertically. Drum plotters hold the carriage bar in place and roll the paper back and forth on a drum. Paper movers do away with the drum and hold the paper on both sides with pinch wheels that roll the paper back and forth. Because the pinch wheels are much lighter than a drum, they can be run by a smaller, less expensive motor.

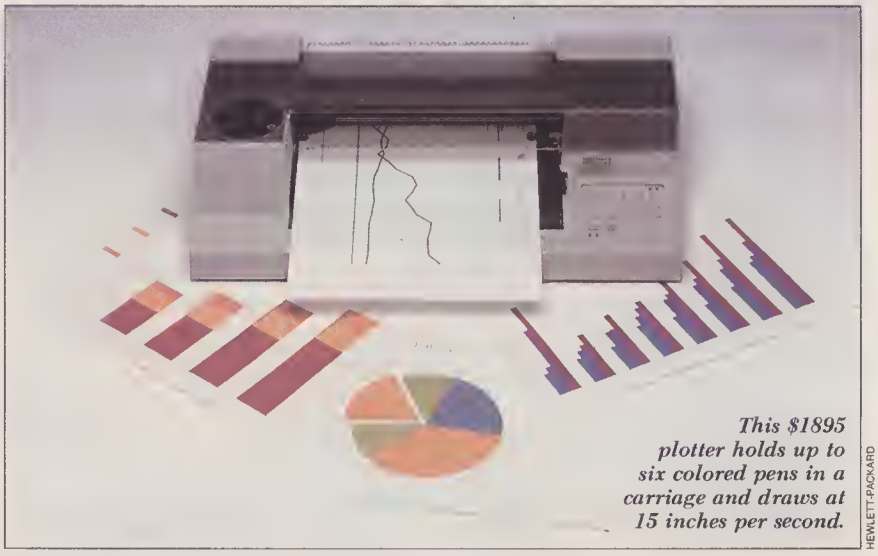
Regardless of type, all plotters have one motor for X movement, and another for Y movement, as well as a solenoid to raise and lower the pen. Stepper motor–based plotters can draw increments in only eight different directions: back and forth horizontally, up and down vertically, or in any of the four 45-degree diagonals. Although they appear to be drawing curves, these plotters are actually producing approximations of curves formed by straight-line segments.

Plotters using dc servomotors have more freedom of movement: they can plot straight-line segments between any two coordinates. Still, they must also define curves by a long series of straight-line increments. Before the use of on-board microprocessors, the host computer had to generate and transmit long strings of data that specified each increment.

In today's desktop plotters, the on-board microprocessors generate these data strings themselves when so instructed by high-level commands from the host computer. Host software to drive the plotters can be purchased off-the-shelf or can be user-written.

Regardless of its source, the graphics software must interface to the plotter's internal device language. Unfortunately, different brands of plotters use different plotting command languages, complicating the task of writing graphics software for the host. To help alleviate this problem, plotter manufacturers have developed industry-standard device-driver subroutines. These allow a plot to be defined in terms of coordinates, symbols, lines, and other characteristics. The device driver converts these to the plotting command language, which the host computer transmits to the plotter.

To convert the command language to the final hard-copy representation requires two steps. *Controller processing* translates the commands into binary vector data, which consist of the ones and zeros that specify the end



This $1895 plotter holds up to six colored pens in a carriage and draws at 15 inches per second.

HEWLETT-PACKARD

by Bob Hirshon

points of each increment, as well as coding for other simple plotter commands, such as "pen up" and "pen down." *Plotter processing* then translates the vector data into pulses that drive the plotter hardware. In high-end plotters, these functions may be handled by two independent microprocessors; less-sophisticated plotters may use only one.

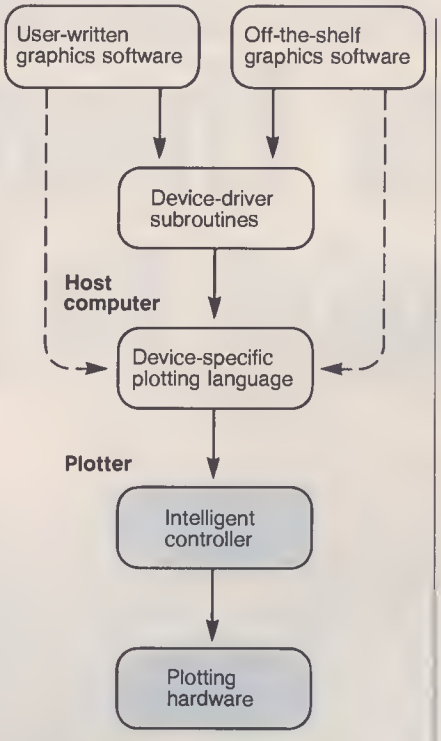
In addition to breaking high-level commands down into binary vector data, controller processing may provide other sophisticated functions. Resident in the microprocessor will be subroutines for commonly used functions, such as circles and arcs, allowing the microprocessor to quickly output the binary data for these lines upon receiving the proper high-level command. Subroutines for scaling (enlarging or reducing), windowing (drawing only a section), and rotating the plot may also be included, as well as schemes for detecting and correcting transmission errors.

In plotters using stepper motors, the plotter processing function converts the binary vector data into electrical pulses that translate into discrete steps of the pen. Higher-end plotters use dc servomotors. For these devices the electrical signals control motor speed and duration.

Some plotters employ closed-loop position-sensing systems, in which the motor continuously outputs how far it has moved. An analog-to-digital converter translates this information to digital form and sends it back to the microprocessor. The latter can then continuously compare the commands it sends the motor with the position information the motor sends back, to ensure that the pen moves to its proper destination.

Although the computing power of intelligent plotters boosts their ability to process commands, their response to those commands is still determined by mechanical considerations, in terms of both plotting quality and speed.

Four variables determine plotting quality: mechanical resolution, addressable resolution, accuracy, and repeatability. Mechanical resolution is the shortest distance a plotter can move its pen. In stepper motor plotters, this equals a single step, typically about 0.1 millimeter (0.004 inch). In dc servomotor plotters, it equals the shortest pulse to which the motor is designed to respond, resulting in a segment as short as 0.025 mm (0.001 inch).



Running either off-the-shelf or user-generated graphics software, the host computer produces high-level plotting commands that instruct the plotter's internal controller. The host software can produce the device-specific plotting commands directly, but will generally use industry-standard device-driver subroutines. These permit the plot to be defined in terms of coordinates, symbols, lines, and other characteristics.

Addressable resolution is the smallest move the user can specify in his program. For stepper motor plotters, it is usually equal to mechanical resolution. For dc servomotor plotters, mechanical resolution is so fine that specifying every segment would create an impractical burden on the software. Therefore, addressable resolution is usually fixed at some greater increment size, generally about 0.05 millimeter (0.002 inch)—finer than stepper motor–based plotters but not as fine as is mechanically possible.

Accuracy is a measure of how precisely a plotter can place one point with respect to another. If a user commands a plotter to draw a 10-inch line, and he then measures the line with a ruler, the difference is determined by the plotter's accuracy. This is an especially important parameter for scale drawing applications such as cartography, in which the final plot will be measured, but less important for most business applications. Accuracy for desktop plotters is usually around 0.1 mm.

Repeatability is a plotter's ability to return to a previously plotted point. A plotter with perfect repeatability would be able to draw a graph and then flawlessly retrace it backwards if the bit-stream were reversed. Today's desktop plotters can be expected to replot points to a precision of 0.1 mm.

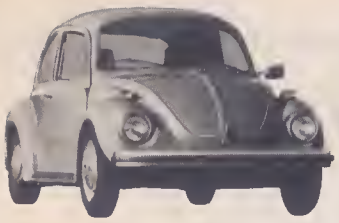
Desktop plotters have probably reached their practical limits in resolution, accuracy, and repeatability. Already the higher-resolution plotters move in step sizes finer than the human eye can distinguish. And even the lowest-resolution plotters have several times the resolution of the typical business computer display, so plotter output will always be sharper than the display image.

But while plot quality is probably as good as it needs to be, the time required to draw a plot could still be improved. Two mechanical factors—pen speed and acceleration—determine how fast a plotter can draw. Maximum pen speed is typically 5–20 inches per second in desktop plotters. Diagonal pen speed, generated by the X and Y motors simultaneously, is faster than single-axis pen speed.

Acceleration, measured in G's, or multiples of 32 ft/sec^2, refers to how long it takes the pen to reach top speed, and varies in desktop plotters from 1 to 3 G's (32–96 ft/sec^2). Acceleration is extremely important when plotting numerous small vectors, as are required for text. In these applications, plotters may never come close to reaching their top speed.

Electronic constraints, including the time needed to receive and process data, also limit a plotter's output rate. As a result of both mechanical and

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electronic factors, plotters require anywhere from two minutes to produce a simple plot to 20 or more minutes for a complex one. Filling in areas with color especially slows the plotter. (Single-pen plotters require pen changes for multicolor plots, further extending production time. Plotters with two or more different colored pens eliminate this extra delay.)

Plots requiring graphics mixed with blocks of text, which are among the most important tasks for business applications, are the most difficult, time-consuming tasks for plotters. Consequently, business computer users are increasingly considering alternatives to pen plotters. These alternatives mirror a technological shift that has already occurred in graphics displays.

Over the past several years, raster-based displays, which form images from a series of scan lines, have all but replaced vector-based displays, which draw images point to point. Raster displays more easily fill in large blocks of color, easily mix text and graphics, and require the same amount of time to display any image, regardless of complexity. Raster-based plotters are encroaching on the pen-plotter market for exactly the same reasons.

These devices are generally termed printer/plotters, because they produce graphics or text with equal facility. Because they form images from rows of dots at a resolution no greater than 200 points per inch, line quality is far lower than that of pen plotters. But plot speed is faster, and the newest printer/plotters can produce letter-quality printing. Consequently, they are gaining popularity in office applications in which speed is paramount.

There are four printer/plotter technologies: electrostatic, thermal transfer, impact dot matrix, and ink jet. Electrostatic devices have a line of electrode nibs running the width of the paper. These selectively deliver charged dots to special charge-retaining paper. The paper then passes through oppositely charged toner that is attracted to the dots and fixed to the paper by either heat or pressure.

Electrostatic printer/plotters are fast, but require special power, and, in desktop units, are limited to one color. Multicolor electrostatic printing has been introduced in large-format printer/plotters, and is expected in desktop machines in the future. Until then, electrostatic devices will find only limited use in business applications.

Thermal-transfer printer/plotters likewise have a row of print nibs that run the width of the paper. Thermal-transfer units, however, deliver spots of heat, rather than electrical charge. The heat melts dots of wax-based pigment from an ink sheet lying between the print nibs and the paper. Overlaying and interspersing dots from three process-color ink sheets allows printing in full color. Thermal-transfer devices require special paper, print small images, and cost $6000–9000.

Many conventional impact dot-matrix printers are now capable of producing graphics as well as text. Some, using multicolored ribbons, can even print in color. They print by means of needle-shaped hammers that strike a typewriter-style ink ribbon, driving it into the paper. These devices may use a matrix of dots so fine that the print is almost typewriter quality. However, graphic output remains draft, not presentation, quality. One company, Envision (San Jose), offers a dot-matrix color printer/plotter with a built-in vector-to-raster converter. This allows the user to generate graphics with a graphics software package designed for pen plotters, and outputs the results on the raster printer.

Ink-jet machines have print heads consisting of ink-shooting nozzles, switched on and off by piezoelectric transducers under microprocessor control. By delivering process-color drops of ink on command, ink-jet printer/plotters quickly and quietly create full-color images or text. But although these devices have dropped dramatically in price over the past year, and now may be as inexpensive as pen plotters, their output quality doesn't compare with that of equivalent-priced pen plotters.

Do the printer/plotter technologies pose a threat to pen plotters? "It depends on your timeframe," says Bill Manos, product manager for Nicolet Zeta (Concord, Cal.), a manufacturer of middle- and high-end pen plotters. "Right now there's a market for all the other devices. But if you absolutely want that production quality, you have to use a pen plotter."

And Enter's Murray says, "We can't predict the future any better than anyone else, but the pen plotter offers an excellent solution right here, today."

Bob Hirshon is editor in chief of Memory Update, *a new journal of mass memory technology, and contributing editor for* Digital Design *and* Electronic Imaging *magazines.*

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MAKING COMPUTERS EASY TO USE

Better software and hardware improve the interface

With more sophisticated software and improving hardware, microcomputer designers at last have the freedom to develop new interfaces—new ways of giving a computer information and of receiving information from it. Earlier computer concepts are showing their age as modern visual interfaces begin to appear in the latest products.

Interface design has always been torn by fundamentally conflicting demands, particularly ease of use versus ease of programming: The simplest interfaces to use are also the hardest to program.

Traditionally the choice has been ease of programming. Thus the operating systems of most computers, whatever their size, use command-line interfaces. In the microcomputer world, such operating systems include Apple DOS, CP/M, and MS-DOS.

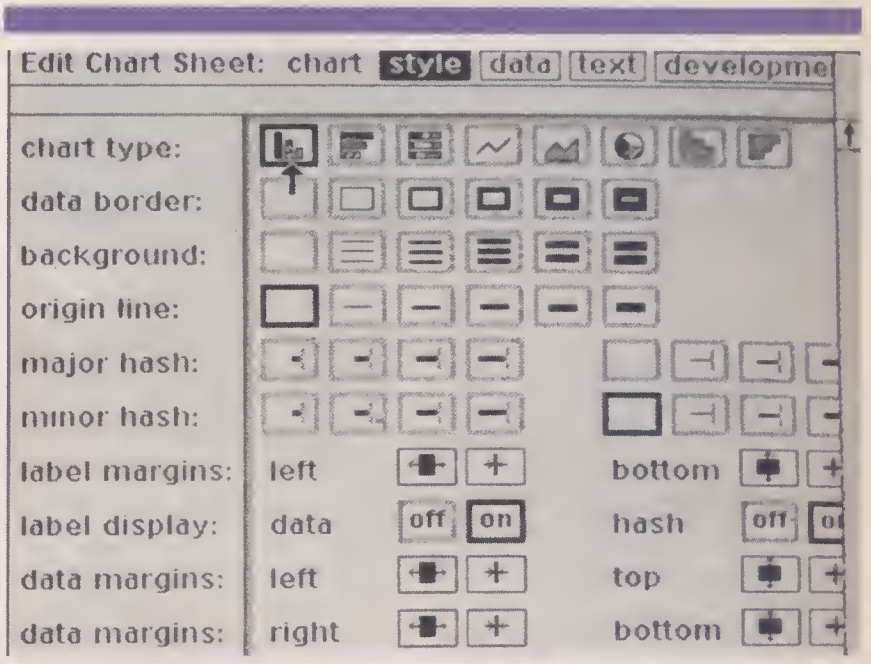
For a new user, command-line interfaces pose a major hurdle, as they offer virtually no information; the screen shows A > or something equally cryptic. Because of hardware restrictions, most efforts to improve them have been limited to additional on-screen text, in the form of prompt lines or menus (see "Traditional interfaces").

For certain tasks, command-line interfaces will survive a long time. For example, a programming language is really a command-line interface with hundreds or even thousands of variations possible at each program step. Some languages could adopt an interface that gives advice or offers choices in specific situations—telling you to close a loop, for instance. Similarly, command lines will continue to be used to ask for information from databases (database query systems); the query options are too complex for menus.

New command-line interfaces will be able to understand natural language—ordinary English—eliminating the need for rigid codes or syntax. The CLOUT interface for MicroRIM's (Bellevue, Wash.) Rbase 4000 database, which can learn new words and phrases, is the first practical microcomputer product of this kind. But natural language isn't suitable for many common computer functions; we should never have to type

DELETE THE NEXT SENTENCE

Old-fashioned interfaces on large mainframe computers present no insuperable problems for data processing specialists trained to use them. When a microcomputer user must access the mainframe, a modern interface on the micro can act as a buffer, converting the user's commands into the form needed by the mainframe. Likewise, modern interfaces have increased access to comprehensive dial-up databases, which have generally been used only by specially trained librarians.



Interleaf's Office Publishing System is the first visual interface running on Unix. A mouse-controlled pointer selects from icons and menu items (above). Pointing at arrows to the right of a menu entry brings up submenus (left); this example shows three layers of submenus.

by Cary Lu

The first important dial-up database buffer program, In-Search (Menlo Corp.–Santa Clara, Cal.) for the Dialog database, is far easier to use than Dialog's own command structure.

Command-line interfaces have survived partly because they will run on any kind of computer terminal, even one without a video screen; a text-printing terminal alone suffices. Today, microcomputers with bit-mapped screens (on which each point has its own memory location) have sufficient graphics resolution to display any image. Such hardware developments herald the end of the command-line interface for the average user; operating systems like CP/M and MS-DOS should be the last of their type.

Unix, widely touted as the standard operating system for the next generation of microcomputers, has a command-line interface even more cryptic than most. To be sure, anyone can learn to use Unix, but then anyone can learn Greek, too.

Unix may have enough vendor and programmer interest to become an important standard, but only if its interface is so thoroughly buried that ordinary users—and even most experienced users—never encounter it. Several "shells" already put a menu-driven interface around Unix; you select your options from menus, and the shell translates your selections into Unix commands. Although helpful, such interfaces will give way to graphics-driven, or visual, interfaces for Unix; AT&T, Convergent Technologies, and Microsoft are all working on these.

Visual interfaces owe their development mainly to Xerox's Palo Alto Research Center (PARC), which produced the Xerox Star, the first commercial computer with such an interface. Moreover, former PARC employees at Apple were instrumental in putting the visual interface on the Lisa and the Macintosh. Many other hardware and software products incorporating key features of the visual interface are now beginning to appear.

A visual interface is more intuitive and therefore much easier and quicker to operate than older designs. The essence of the visual interface is that you manipulate icons—graphic symbols—rather than type commands. To copy a disk file onto a second disk with a command-line interface, you must type, without error,

PIP B:=A:TEXTFILE.EXT

With a visual interface, you merely point at a file icon and move it to an icon for the second disk. A mouse (a device rolled on a surface to control the cursor on the screen) is the most common pointing device for selecting and moving the symbols.

Not every command can be put into icons. Symbols work best for choices that have clear visual attributes, such as left and right text margins. But what is an icon for "search"? All visual interfaces therefore combine icons and menus. The latter are typically "pulled down"; only the heading is visible until selected, then the rest of the menu appears. Because pull-down, or pop-up, menus take up only a portion of the

Traditional interfaces

Interfaces aren't too difficult to learn when you have only a few command choices; they get difficult when you have hundreds of choices. With a word processor, for example, you may want to enter or edit text, adjust the page format, search for a word, set tabs or margins, or print. How should a program present these choices?

The classical methods have been command lines, menu initials, menu words, and full menus. Command lines require a lot of training and memorization, and fluency comes slowly. They work well only for experienced regular users; rarely used features are easily forgotten.

A command-line interface is almost no interface at all. On the screen, you see only

A>

The computer sits, waiting for a command. You have no information about your choices. If you don't know what to enter, you will have to search through a manual to find out. In principle, the software can recognize any form of keyboard input, so the range of possible choices is enormous. In practice, typical software recognizes a few dozen commands with modifiers. Thus you type DIR for a file directory, DIR B: for the directory of disk drive B, and so on.

As a step toward helping users, some interfaces offer a menu of initials to remind you of your choices (the example is from SuperCalc):

Enter: A, B, C, D, E, F, G, I, L, M, O, P, Q, R, S, T, W, X, Z

You have to know, for example, that *E* stands for edit, *M* for move. Menu initials are only a little less cryptic than command-line interfaces.

Somewhat easier are the menu-word interfaces. In this example from Lotus 1-2-3, the lower line explains the selection (*Global*):

Global Insert Delete Column width Erase Titles Window Status
Set worksheet settings

You still have to read the selections, and since everything appears in the same typeface, there is little visual distinction between the menu words and your data.

Full menu-driven interfaces generally take up the entire screen with menu choices:

___ Copy a file **___ Run a program**
___ Edit a document **___ Print a document**

Such interfaces work well for new users, but since only a few choices can appear on the screen at a time, you may have to page through several layers of menus to get something done. This can drive experienced users up the wall. The best menu-driven systems let the expert bypass the menus.

To make interfaces easier to deal with, many programs offer help screens listing the possible choices. Modern help screens are context-sensitive, providing information about the choices available at a given point in the program. Although using help screens is usually faster than looking something up in a manual, they are still cumbersome. Many programs contain dozens of help screens, and you may have to page through them for the information you need. Moreover, most help screens, like full menus, take up the entire screen, obscuring your work.

Function keys are another interface aid. Commands can be assigned to them either by the software developer or, in most systems, by the user.

screen at a time, they don't obliterate your working area. And by pointing at different menu headings in turn, you can scan the menus much more quickly than with older full-screen designs.

Improved screen graphics can display different typefaces, sizes, and styles, giving individuals five hundred years of typography once reserved for printing presses. By using different typefaces, software designers can aid us in distinguishing commands, help information, and our own data.

Most visual interface packages include windows, which let users divide the screen into several parts. Although useful in some situations, windows show just how small a microcomputer screen really is. They work far better with large screens that show a full page (60 lines of text) or, as with the Xerox Star, two pages. Yet such big screens, particularly in color, are hard for current microprocessor chips to manage on their own. More computers will incorporate separate processors dedicated to handling graphics; some of the next generation of microprocessor chips will include special graphics processing in microcode so they can manipulate the screen even faster.

Those who complain about visual interfaces generally haven't used them. Some assert that they know how to read and hence don't need icons, but everyone can identify visual symbols faster than they can read text. What are punctuation marks if not graphic symbols? Would critics prefer to return to the age when manuscripts lacked periods or commas? Some people seem to argue that a computer is no longer a computer when it becomes easy to operate.

Still, no interface is perfect for all situations, and visual interfaces have their problems. They are slow for some operations. Common commands, such as "undo," just take too many steps. You must move your hand to the mouse, point at a menu heading, pull down the menu, and choose the command. So despite some objections from the purists among interface designers, most visual interfaces add function keys for common commands. On the Macintosh you can simply press the command key and *Z* for "undo."

Today's products merely point the way; there will be much more development of interfaces in the next five years than in the previous forty. □

Cary Lu is microcomputer editor of HIGH TECHNOLOGY.

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by Dwight B. Davis

SPORTS BIOMECHANICS: OLYMPIANS' COMPETITIVE EDGE

To eyes previously dazzled by state-of-the-art computer graphics and animation, it doesn't look like much. A lone stick figure strides silently across a display screen, with a peculiar gait that only a few would recognize as that of a competitive race walker. But the spindly character's rudimentary appearance belies its deeper significance: Over the past several years, this multitalented stick figure has become the symbol of sports biomechanics, an emerging movement in sports analysis and training. Though still in its formative stages, this field has already aided numerous athletes, many of whom will compete in this summer's Los Angeles Olympic Games.

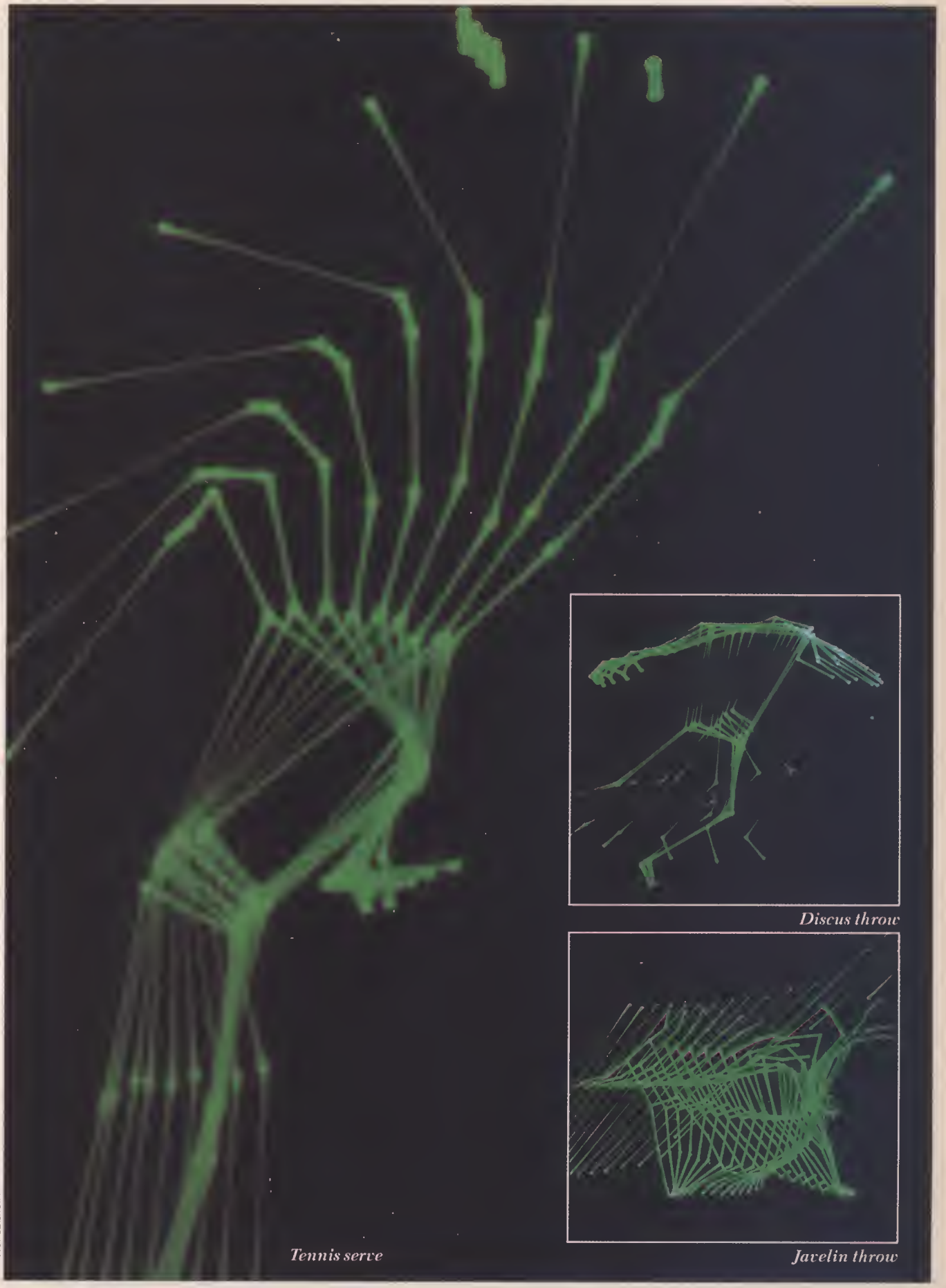
In essence, biomechanics takes the principles of engineering and applies them to the human body. Within this realm the simple stick figure illustrates the essentials of an athlete's motion and technique. Created from high-speed films of performing athletes, the figure is just one aspect of sports biomechanics, which uses film, video, and electronic techniques to measure performance and suggest improvements.

Swimmers, for example, can use biomechanics to improve hand and arm leverage, kicking power, and body position to propel themselves with optimal efficiency. Biomechanics' sphere of influence extends even into team sports such as volleyball. Here the entire team is viewed as a single biomechanical system, and position analysis of the various players helps determine the best setup for certain game situations.

Initially, biomechanics research focused on medical applications such as linking improper walking techniques with physical maladies. But researchers have long recognized that biomechanics holds the potential to help the human machine perform athletics with more efficiency, speed, and power. Over the past decade, as equipment for data collection and analysis became more sophisticated, sports biomechanics began to blossom. This fruition has been aided by a growing academic respect for the field.

"Typically, sport was not considered an area of serious research, and most deans of engineering schools weren't particularly enthralled about their faculty studying it," says Charles Dillman, who taught biomechanics at the University of Illinois and at Pennsylvania State, and who now heads the U.S. Olympic Committee's biomechanics lab in Colorado Springs. During the 1970s, as interest in amateur and recreational sports grew, so did the impetus to apply engineering to athletic techniques and equipment, Dillman says.

Researchers apply engineering principles to analyze and improve athletic techniques



Tennis serve

Discus throw

Javelin throw

DAN MCCOY/BLACK STAR

Eventually a commercial market may develop for biomechanical analysis in the most popular participant sports, such as tennis and golf, and for professional sports such as football and baseball. But for now, activity is largely confined to research by specialists in Olympic sports.

Despite its newfound respectability, however, sports biomechanics has significant hurdles to overcome. Foremost is a lack of equipment designed specifically to aid biomechanical research. The field is simply not large enough to attract the attention of manufacturers, so most of the equipment has been jury-rigged for sports applications. On the human side, graduate schools have only recently begun to produce trained personnel. Biomechanics requires knowledge of such varied disciplines as physiology, engineering, computers, and mathematics, "and not everybody can be an expert in all those fields," says Dillman.

As for the benefits that athletes gain from biomechanical analysis and training, Dillman is cautious in his claims. "There are athletes who say that our biomechanical suggestions have helped them make improvements," he says, "and we wouldn't be doing this unless we felt we were making a contribution. But biomechanics is just part of the complete system. We now have sports physiology and biomechanics combined with good coaching, good facilities, dedicated athletes, and financial support. Without any one of those components, the system wouldn't operate."

Olympic lab. The USOC's biomechanics lab was established in the late '70s under the guidance of Gideon Ariel. Recognized as one of the pioneers in sports biomechanics, Ariel now serves as president of the Coto Research Center (Trabuco Canyon, Cal.), a commercial biomechanics laboratory.

Although commonly used to measure the body and foot forces of runners and walkers, force plates have other sports applications. Here plates monitor the component forces produced during a judo throw and a volleyball player's leap.



B. PAYNE/BLACK STAR



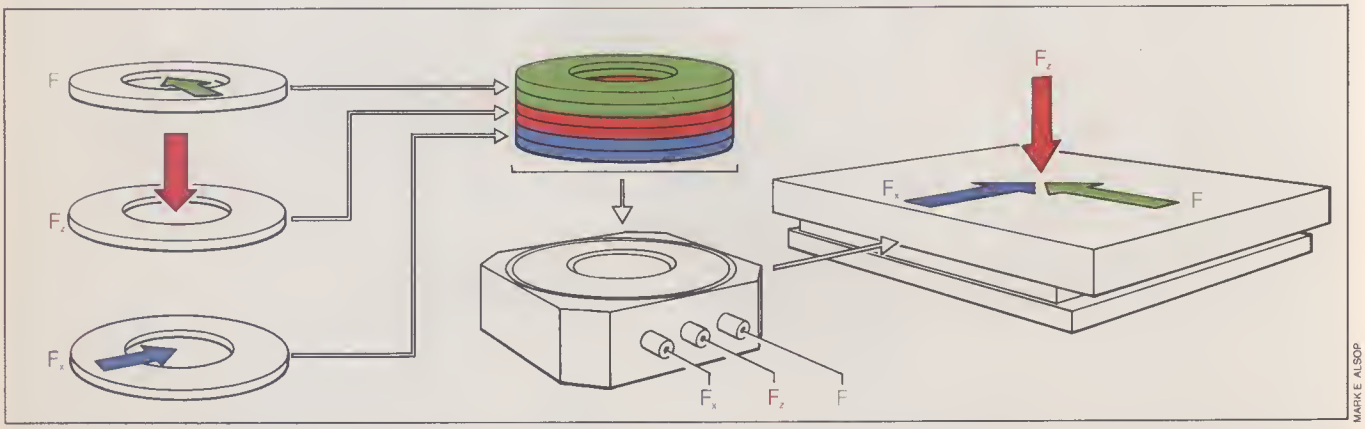
G. BIRCH

The Olympic lab—part of the USOC's sports medicine program, along with sports physiology, clinical services, and education—is considered by most experts to be one of the best-equipped biomechanics facilities in the world. Most of the equipment is state-of-the-art and is donated by manufacturers, often in exchange for feedback from the lab about equipment design and application.

Although Dillman believes the U.S. is second to none in its equipment technology—makeshift though it may be—he says the Soviet Union probably has the best group of sports scientists in the world. "But the Soviet researchers aren't too good at communicating with the coaches," he says, adding that in terms of implementing biomechanics research, no one yet matches the East Germans. But Dillman maintains that the U.S. has "the potential to combine both of these elements and become the best in the world."

Aside from conducting its own research, the USOC lab commissions and coordinates research at various other biomechanics facilities, mostly at universities, throughout the country. This way the Olympic Committee is able to tap the expertise of researchers who specialize in different sports. Only five or six of the more than 30 Olympic sports (winter and summer) are studied primarily by the Colorado Springs lab. Within these sports, the lab focuses its attention on a selected number of "elite" athletes thought to be likely competitors in the Olympic Games.

Requests for specific types of biomechanics research are submitted to the USOC lab by the national governing bodies of the various sports. When results are obtained, the lab makes them available to the appropriate governing body, which then disseminates the in-



MARK E. ALSOP

Force plates exploit the piezoelectric effect, through which certain crystals produce an electrical charge when stressed. Disks of quartz are cut to be sensitive either to downward pressure or to shear; groups of these disks are fitted into the force plate in such a way as to measure forces that travel downward (F_z), side to side (F_x), and forward and backward (F_y). The system also measures the instantaneous point of force application and the twisting force about the vertical axis. (Source: Kistler Instrument)

formation to the coaches and athletes. The critical role, according to Dillman, is played by coaches.

"It's a typical misconception that scientists are working directly with the athletes," he says. "That's not true. None of our recommendations, no matter how good, can be implemented instantaneously. So the coach is still the central figure in the system for improving athletic performance, because it's the art of implementing the scientific information that is really the key."

Equipment galore. To give coaches useful information, biomechanists use an array of equipment to collect performance data. This equipment can be grouped into two major categories: electronic and film/video. Electronic equipment directly measures movement and forces. But because the athlete must either wear or come into direct contact with elements of such systems, they are most often used only in the laboratory. To collect biomechanical data from actual competition, researchers must rely upon unobtrusive high-speed film or video. Data analysis is carried out with the aid of computers, which typically run custom-written software.

Probably the most established piece of electronic equipment is the force plate. Depending on the sport, an athlete stands on, walks over, or runs across a plate embedded in the laboratory floor or racing track. For both static (standing) and dynamic (moving) tests, the plate measures various force components produced by the athlete. The USOC lab uses plates manufactured by Kistler Instrument Corp. (Amherst, N.Y.) and by Advanced Mechanical Technology (Newton, Mass.).

To measure forces, the plates exploit the piezoelectric effect, which causes an electrical charge to appear on the surface of certain crystals when they are mechanically stressed. For example, quartz sheets can be cut so they are sensitive only to downward pressure or to shear in a single direction. Layers of such sheets can be arranged in force plates in such a way as to be sensitive to downward, forward-and-backward (medial), and side-to-side (lateral) forces (see illustration, p. 36). Moment about a vertical axis can also be determined. Electrical charges produced by these force transducers are converted into voltages, which can be recorded and plotted. Kistler claims its force plate is sensitive enough to detect the heartbeat of a person standing on it.

In a static application of this technology, the USOC lab measures the movement of archers and marksmen who shoot while standing on the force plates. "We're very interested in studying the movement patterns just before the shot," explains Janet Dufek, a research technician. "For this application, the forward-backward and side-to-side forces are more important than the vertical force."

"For shooting and archery," says Dufek, "we're finding that it's not good practice to compare athletes or to model them after a world champion." For example, graphs of two archers show them leaning in the opposite direction from each other, with one exhibiting greater overall stability. But in the two shots graphed, the scores were the same: 9 out of a possible 10. "Regardless of what movement or lack of movement occurs," concludes Dufek, it's best to aim for "consistency within the subject from shot to shot."



A race walker performs while wearing the Langer Electrodynogram. The EDG's waist-mounted data collector records the signals from seven force transducers placed on the sole of each foot.

But in other sports, such as running and jumping, the goal tends more toward emulating the technique of top performers. Biomechanics must work in concert with physiological capabilities and mental attitude in athletic competition; hence it's conceivable that a world champion might have a less than perfect biomechanical technique. But Dillman says that, as a rule, top athletes vary only slightly in their methods and that biomechanics theory tends to suggest techniques that these athletes are already using. "The top athletes do things in common that you can logically back up by applying principles of mechanics," he says. "So modeling after what the best in the world are doing has some justification."

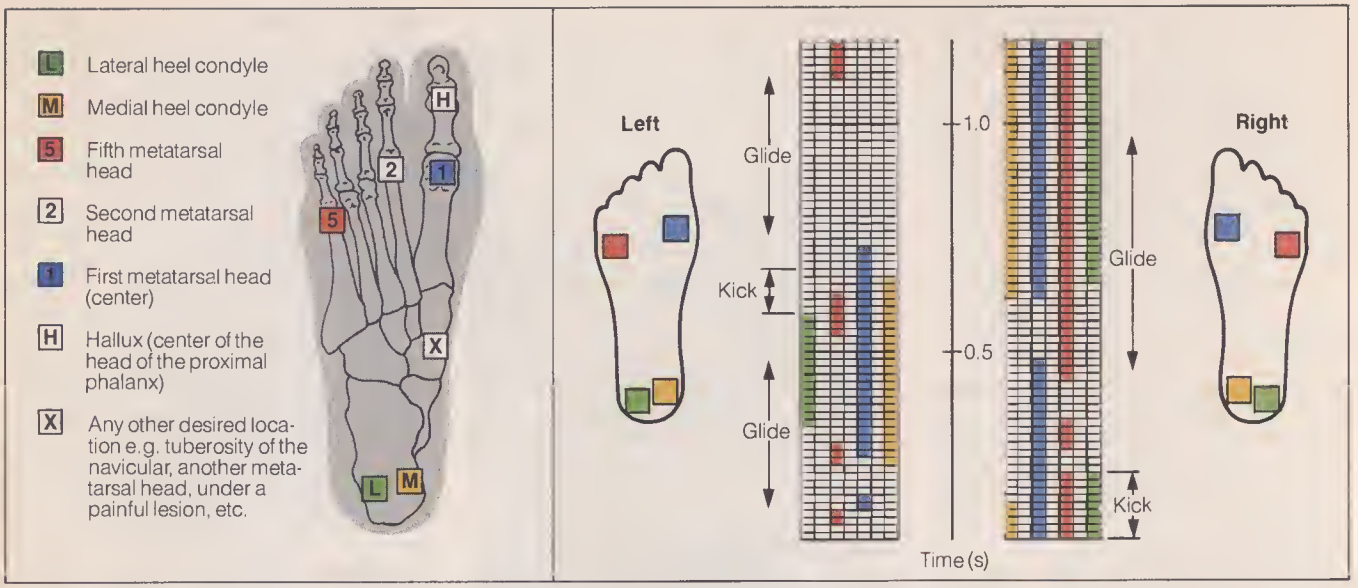
Portable sensor. Force platforms are an important source of data for dynamic sports as well as static. A runner's or race walker's foot striking the platform provides information about the development and amount of force generated along the foot and about potential problems such as excessive sideward rolling (pronation) of the ankle joint. But there are limits to the practicality of force plates in dynamic applications.

A force plate large enough to measure just a single foot strike can cost $50,000. Long force platforms or series of small ones that can measure complete strides are often prohibitively expensive. Thus a complete evaluation may require that an athlete make several passes over a small pad, accurately striking it a number of times with first the right and then the left foot. The separate data are then compiled to yield a representative full stride.

A relatively new device from Langer Biomechanics (Deer Park, N.Y.) attempts to remedy some of the force plate's shortcomings. The Langer Electrodynogram (EDG) consists of 14 transducers that adhere to the soles of the feet (seven per foot), lead wires, and a data collection pack that is worn around the waist. Developed for podiatric gait and ambulation studies, the EDG has been a boon to the USOC lab, especially in the analysis of race walking.

The EDG is worn by an athlete either in a laboratory or in the field. To initiate a test, the athlete pushes a button on the data pack (or the test may be initiated remotely via telemetry). After a one-second delay, the EDG collects data for five seconds. This is long enough to measure several successive strides of a race walker.

Unlike the force platform, the EDG measures just one force component: direct pressure. And while force platforms detect the forces generated



With pressure-sensitive transducers placed under seven prominences of each foot, the Langer Electrodynogram directly measures foot-generated forces. Here the outputs from four transducers on each of a cross-country skier's feet give information about the duration and location of the applied forces. The graph shows that the skier exerts more lateral heel force with the right foot than with the left during the kick phase. This indicates overstriding or overstrength in the right leg or a lack of either in the left.

where the shoe meets the surface, the EDG measures foot forces within the shoe. These measurements tend to be more useful than the force platform data, asserts Michael Polchaninoff, Langer's VP of technical R&D and the developer of the EDG.

The EDG foot sensors are placed under seven bony prominences that biomechanical analysis has shown to be key areas of force transfer (see illustration). "The detail available from the EDG, because of its isolated locations, is specific to the function and the anatomy of the foot," says Polchaninoff. He points out that two athletes with very different feet could produce similar force plate measurements once their bodies' force had been transferred through shoes containing corrective orthotics. "On the other hand, there are applications where you need to know about things like shear, which we cannot measure directly," he admits.

Even though it measures only direct pressure, however, the EDG can indicate motion such as pronation. The shifting of force from sensors on one side of the foot to those on the other side gives information about foot rolling, for example. And sensors placed in nonstandard locations like the side of the foot can measure lateral forces.

Each EDG sensor consists of a disposable adhesive component and a permanent component attached to the wire leads that link to the waist-mounted force-data collector. Together the two sensor components form a transducer system based on resistive principles. A force imparted to each sensor produces a corresponding electrical resistance, which is measured by the waist recorder. The information can be unloaded onto a cassette tape, permitting numerous field tests, or can be fed directly into a microcomputer dedicated to analyzing the data. Langer has a database of parameters for normal nonathletic walking. But because race walking and running results vary considerably from this standard, the company is relying on the Colorado Springs lab to generate databases for athletic applications.

At some point the fairly bulky EDG waist pack may be eliminated and replaced with a telemetry system that would broadcast continuously to a nearby data collector. The USOC lab is experimenting with various telemetry applications in other fields, but director Dillman says the technology is far from perfected. And Polchaninoff notes that while it is possible to switch the waist pack on via telemetry, "it is difficult to transmit data at the rate and reliability we need over 14 channels."

Optoelectronics. Sports biomechanists care not only about the body's exerted forces but also about its movement. One piece of equipment—the Selspot, from Selcom (Valdese, N.C.)—consists of one or more cameras sensitive to infrared light. The cameras detect infrared waves produced by a variable number of light-emitting diodes (LEDs) that are attached to specific points on an athlete's body. The LEDs are turned on and off successively by an "administration unit," which also coordinates the camera sampling and transmits data to a computer for analysis. The cameras track the position of each LED as it moves across the field of view, producing data that can be used to automatically generate stick figures on a computer screen and parameters such as position, velocity, acceleration, center of mass, and body angles.

The latest version of the Selspot can support up to 16 cameras and 120 LEDs. With one camera and one LED, the system produces 10,000 samples per second. If 10 LEDs are used, flashing sequentially, the sample rate for each is 1000 per second. A single camera gives two-dimensional data on the athlete's movement; two or more cameras positioned properly can give three-dimensional data.

The USOC lab uses the Selspot system to measure apparatus movement as well as body movement, says Dufek. "We can apply the diodes to various points on the athletes or on the instruments they use, such as a marksman's gun, an archer's bow, or a weight lifter's bar. It gives us immediate feedback on those points in space, which we can then calibrate and analyze." Like the other electronic systems, however, the Selspot would be impractical in actual competition.

Film digitization. Traditionally, biomechanists have depended on high-speed film to capture detailed images of athletes in competition. For most sports, 100-frame-per-second film suffices, says USOC researcher Dufek, although sports such as golf, tennis, and baseball may require higher-speed film.

The USOC affiliate laboratory at the University of Kentucky, in Lexington, uses high-speed film to record and analyze the performance of sprinters and hurdlers in competition. The Kentucky researchers typically employ three

cameras—one for panning and two for focusing on a specific area from different angles. By an algorithm called direct linear transformation (DLT), it's possible to get three-dimensional data from two fixed cameras. But although the Kentucky lab is equipped to calculate DLT, the track events being studied don't lend themselves to such analysis, says associate professor Ralph Mann, a chief biomechanics investigator.

The DLT algorithm permits only limited flexibility in camera angles and distances—parameters that are difficult to meet in setting up the equipment at a track meet, Mann explains. Some relatively confined events such as the high-jump and the hammer throw can be more easily filmed for DLT analysis, he says, "but the usual problem for us is that we have eight athletes competing in eight different lanes. Because of the situation's complexity, we can only perform a two-camera, two-dimensional analysis."

While a frame-by-frame observation of the film can yield qualitative biomechanical information to the trained eye, the images must be digitized and stored in a computer to produce quantitative data.

To determine the coordinates of an athlete's body as it performs, the high-speed film is projected frame by frame onto a large digitizing table. The USOC lab uses a table from Talos Systems (Scottsdale, Ariz.) with a resolution of 1000 lines per inch. The researcher uses a cursor instrument to enter specific coordinates from the image, such as toe, heel, knee, hip, and shoulder points. As the points are entered, a corresponding stick figure appears on a Megatek (San Diego) graphics display. At this stage, the figure gives a visual confirmation that the data have been entered in the proper order, ensuring their reliability. This process is then repeated, frame by frame. Although the manual entering of body coordinate data is tedious, no automated method exists. (The Selspot LED system can automatically generate stick figures, but it can't be used in competition.)

Stick-figure generation and the underlying data analysis are performed with software written by the lab's programmers and run on a donated Eclipse S/250 computer, made by Data General in Westboro, Mass. (The programs originally developed by Gideon Ariel are no longer used at the USOC lab because equipment modification has made them incompatible with the current setup.) The lab is also testing parts of a commercial software package developed by Herbert Hatze, a mathematician who directs the Austrian Institute of Sport in Vienna. Hatze's $30,000 Biomliv package covers functions ranging from basic kinematics to computer simulation "and represents the state of the art in mathematical analysis of the human body," says Dillman.

One of the USOC lab's main goals is to interface its own computer programs to the Hatze software, says Mark Fenton, a research assistant at the lab. But even with the lab's present custom software, biomechanists can move the stick figure automatically or manually, view every frame or selected frames, calculate the center of gravity and superimpose it as a dot on the figure, and determine the angles of the body segments. They can also set bounds for certain parameters, such as the angle of the elbow. If, for example, the angle exceeds 90° at any point, the system can be programmed to highlight the bending arm in a different color.

"We can also look at stride rate and stride length and compare them among different athletes, normalizing by body height," says Fenton. "One guy might make a stride that's 80% of his height, and another might make one that's 95% of his height. To determine which is better, you might compare them with the current world champion."

Fenton, himself an elite-class race walker, believes such biomechanical analysis has helped him improve his technique. Force platform analysis indicated that he decelerated at a certain point in his striding cycle. Analysis of his digitized film image showed that this deceleration was probably caused by a tendency to place his leading foot too far in front of his center of gravity. "I would shift back as I got the foot out in front of me, then pull over and shift forward," he says. "The shift back in the early support phase was probably an inefficiency, causing deceleration."

A race walker's legs should mimic the spokes of a wheel, Fenton explains. They should pass under the center of gravity, impart their downward and backward forces, and propel the walker smoothly forward. By shortening his stride slightly and making other adjustments, Fenton hopes to bring his technique closer to this ideal.



CHUCK O'REAR

A researcher at the U.S. Olympic Committee's biomechanics lab records body coordinates from a film of a race walker. Frames of the film are projected onto a digitizing table, and the circular cursor device enters the position of chosen body points into a computer for analysis and stick-figure generation.

Video momentum. Although high-speed film has long reigned as the premier method of collecting movement data, its dominance may soon be threatened by high-speed video. Video has several advantages over film: It is inexpensive and easy to replicate, gives instant feedback, and records in dim light. Furthermore, two video cameras can record simultaneously on a single videotape for split-screen display of an athlete from different angles. And more people have access to video cassette recorders than to 8- or 16-mm film projectors.

Still, video has one major fault. "Its resolution is horrendous," says Mann

MODELING HUMAN MOTION

by Joseph Alper

Early last year, a young boy with a severe limp walked back and forth in front of a video camera at the University of Wisconsin in Madison. Mechanical engineering professor Ali Seirig sat at a computer display terminal on which the child's image appeared. With a lightpen he made various marks on the image as it moved across the screen. Minutes later, a crude figure—a computer-generated model of the boy's motions—appeared on the terminal, limping just as the child did.

Seirig enlarged one of the figure's legs. Using the lightpen as a scalpel, he began to shorten the leg, simulating the removal of small pieces of bone. After each "operation," the image walked back onto the computer screen. When the figure stopped limping, Seirig typed more commands into the computer; the figure began to run smoothly across the screen. Seirig noted how much bone he had excised from the leg and sent the information to the boy's orthopedic surgeon.

Several weeks later, the child was in the operating room. Normally, the surgeon's experience would have dictated how much bone needed to be removed. But that day he had the information from Seirig's simulated surgery, and chiseled out the predetermined piece. Several months later, the child walked without a noticeable limp for the first time in his life. "I might have achieved the same results without the data," the surgeon said later, "but it was reassuring to first be able to 'try' the operation several times on the computer."

The computer-simulated surgery was the acid test of 12 years' work by Seirig and dozens of graduate students in developing a computerized interactive model of the entire human muscular-skeletal system. "In the early '70s we decided to treat the human body as one big mechanical system and mathematically describe every possible motion that system could make," says Seirig. "We felt that if we could accomplish that, we could design an interactive computer program that would solve all the equations of force and energy and get useful information about how humans move and how to help them when they cannot move correctly."

The model—inspired by some anatomical drawings by da Vinci, which show the muscles, ligaments, and tendons as wires and the bones as rods—can take any human motion and indicate which muscles are acting with what forces on which bones. Seirig assumed that increased tension in the muscles caused the bones to move and that all forces were designed to minimize stress on the ligaments and tendons. He then began to write the hundreds of equations needed to describe human motion and to program a mainframe computer to solve them all.

The equations are very complex, and there are more unknown forces on the muscles and bones than there are equations to determine them. Some of the unknowns were determined experimentally from electromyelographic recordings—which yield data on forces that specific muscles exert on bones—made on the Wisconsin researchers while they moved in front of a video camera. The rest were determined statistically using linear regressions.

The model was only the end of the first stage of this project, according to Seirig. "Now comes the fun part," he says, "where we develop practical applications and see how versatile it really is."

Working with Romolo Savini, an orthopedic surgeon at the University of Bologna (Italy), Seirig hopes to test the model's ability to simulate back surgery, a project similar to the one already completed for leg surgery. This time the researchers want to use computed tomography (CT) data to improve both the model and its simulation ability. "We want to work out the best way of superimposing CT data on top of the video picture of a person's movement," said Savini. "This will give it the accuracy that is essential when operating on a complex structure such as the back, which is much more difficult to operate on than a leg."

One of Seirig's more ambitious projects is to build a microprocessor-controlled muscle activator that would enable paraplegics or stroke victims to walk again. As he envisions it, the device would consist of a tiny computer, no larger than a transistor radio, programmed to send electrical signals through the skin to activate the muscles in the legs. The device could be worn on a belt and would deliver signals to the muscles via pressure-sensitive surface electrodes the size of a quarter and similar to those used with automated hospital monitors. The device would be programmed for several common motions. For example, one button would initiate the proper muscle movements for walking, while another would activate the sequence needed to climb stairs.

The key, of course, is programming the microprocessor so that it stimulates the right muscles to contract with the appropriate force in the correct sequence. While hardly trivial, this has not proven to be the most difficult part of the project. "It turns out that one of the most complicated tasks is stimulating a muscle over a long period of time," says Seirig. "You can't just feed it the same electrical signal all the time, because the muscle's response is not constant."

The researchers had to develop a closed-loop feedback system that could measure the muscle's response to a given signal and then adjust the next pulse to compensate for deviations from a standard response level. They did this by adding to each electrode a sensor that detects the minute electrical signals that echo from a muscle after being stimulated. The sensor feeds its data into a circuit, again contained on the electrode, that modulates the next muscle-stimulating pulse. Each pulse cycle is 0.002 second on and 0.008 second off, during which time the electrode must be readied to deliver a signal of slightly different strength to the muscle.

Seirig expects to finish the electrical circuit design and programming this year and begin testing the device soon afterward. But meanwhile, physical therapists can use the stimulators and a much simpler program to help recondition and strengthen damaged muscles. Using the motion model to analyze a videotape of a person's movements, a physical therapist could determine which muscles needed rehabilitation. Electrodes could be placed over those muscles, and the device could be programmed to energize the muscles so that they were repeatedly contracting—not enough to be bothersome but enough to help them rebuild. Patricia Murray, a rehabilitative medicine specialist at Marquette University Medical School (Milwaukee), is now testing such devices on several patients.

She has also used the program to help a person with an injured hip walk so that the pressure on the hip was reduced while it healed. She supplied the computer with information on the patient's size, weight, and injuries. The model then indicated how the person could reduce the stress on the joint by providing alternative support (a cane). "Before this model, we really had no way to determine what kinds of stresses were put on an injured joint, or even the best way to walk with a cane," explains Murray. "Now we can develop exercises using the model and design better braces that use muscles surrounding the injured joint, which, unlike traditional braces, will strengthen them rather than cause them to deteriorate."

The Wisconsin model treats the human body as a machine, yet results have shown that there are some basic differences. Seirig explains: "One principle of a good machine is that it does the most work with the least amount of energy, but this doesn't hold true for humans. If it did, we would all walk the same, write the same, and so on. Humans are concerned with the beauty of motion, not just its energy efficiency." The two are not mutually exclusive, however. "We tried to apply our model to one of America's outstanding gymnasts," adds Serig, "and it showed that this person was almost as energy efficient as he could be in his movements. But they were beautiful nonetheless."

Joseph Alper, who has a master's degree in biochemistry, is a frequent contributor to HIGH TECHNOLOGY.

at the University of Kentucky. A standard video signal produces about 200 horizontal lines across a TV screen. By comparison, film might have a resolution of 10,000 lines across the same area, Mann says, depending on the resolution of the digitizing table.

The resolution problem of video is related to the field of view, Mann explains. "If you attempt to analyze someone sprinting across a 10-square-foot field of view, any part of the body would have to move about two inches before you got a discrete point difference. That's unacceptable." Mann notes that if the field is limited to one or two square feet, the resolution is a reasonable quarter-inch or so. But such limited fields are feasible only for such applications as focusing on an archer's bow or recording a runner's feet on a treadmill. "For analysis of most competition, we will have to continue to use film for some time," he predicts.

Despite its current problems, however, video holds great potential, according to the Olympic lab researchers. Along with its low cost and ease of use, for example, video allows researchers to imprint simultaneous timing or force data on the videotape. An even greater benefit is that video output can be fed directly to computers for display and analysis.

The USOC lab is experimenting with a component board from Tecmar (Solon, Ohio) that digitizes a video input to an IBM personal computer. The digitized frame can then be displayed on a color monitor. Future developments in pattern recognition and other image analysis techniques might one day permit the automatic location and tracking of body parts in the digitized video frames, says Leonard Jansen, the lab's staff programmer. But for now, the goal is to be able to use an on-screen cursor to manually input the same body-coordinate data now obtained from film projected onto a digitizing table. The screen's cursor could be moved by a mouse pointing device or by a small digitizing tablet and pen.

One drawback of digitized video is that everything in the frame—even extraneous detail—is digitized, resulting in large storage requirements. But this could be overcome by equipment that permits digitization of nothing but the athlete's outline.

Regardless of the equipment used, a growing trend is the integration of data recorded simultaneously by different types of devices. For example, an archer might perform on a force plate while Selspot LEDs record the bow's movement. Depending on the equipment, the recordings can be synchronized by electrical or light pulses or, for events such as shooting, by an audio signal.



U.S. OLYMPIC COMMITTEE

A researcher films a bicyclist performing on a stationary treadmill. The 100-frame-per-second film will be digitized to produce computer-based data, which can be used for a detailed analysis of the athlete's technique.

Central database. Such integration will enable the combination of biomechanical and physiological information. The Olympic biomechanics lab currently performs only a few studies jointly with its sister physiology lab. But an imminent upgrading of the USOC computer facility will help link the two labs more closely.

Data General will soon replace the biomechanics lab's Eclipse S/250 minicomputer with a 32-bit MV-series superminicomputer. The firm is also donating several of its powerful Desktop microcomputers. Dillman, who heads the computer facility as well as the biomechanics lab, says the MV will permit the sports medicine labs to process most of their work on a single machine.

Rather than use one type of microcomputer to analyze the Langer EDG results, another to digitize video, and so on, the new arrangement will facilitate the interchange of data among programs, including those that contain physiological information. The minicomputer will also serve as a central database of information provided by, and available to, biomechanics labs around the country.

The new computer will give electronic access to kinds of information already freely disseminated in print. Biomechanics results collected by the USOC and affiliated labs are published in reports available to anyone, including other nations. "From the Olympic Committee's point of view, there's no secrecy in this material," says Dillman. "There are six or seven countries in the world that can produce the same kind of information as we can. The real key is the implementation, not the uniqueness, of the results."

Only two types of information are restricted: the names of the athletes and particulars on equipment design (for instance, biomechanics data being used to design a new racing bicycle at California State University, Long Beach). So far, however, the USOC lab has done little work in equipment analysis and design. "Ninety percent of the requests from the national governing bodies are related to technique and performance," Dillman explains. "Consequently, that's where most of our effort is right now."

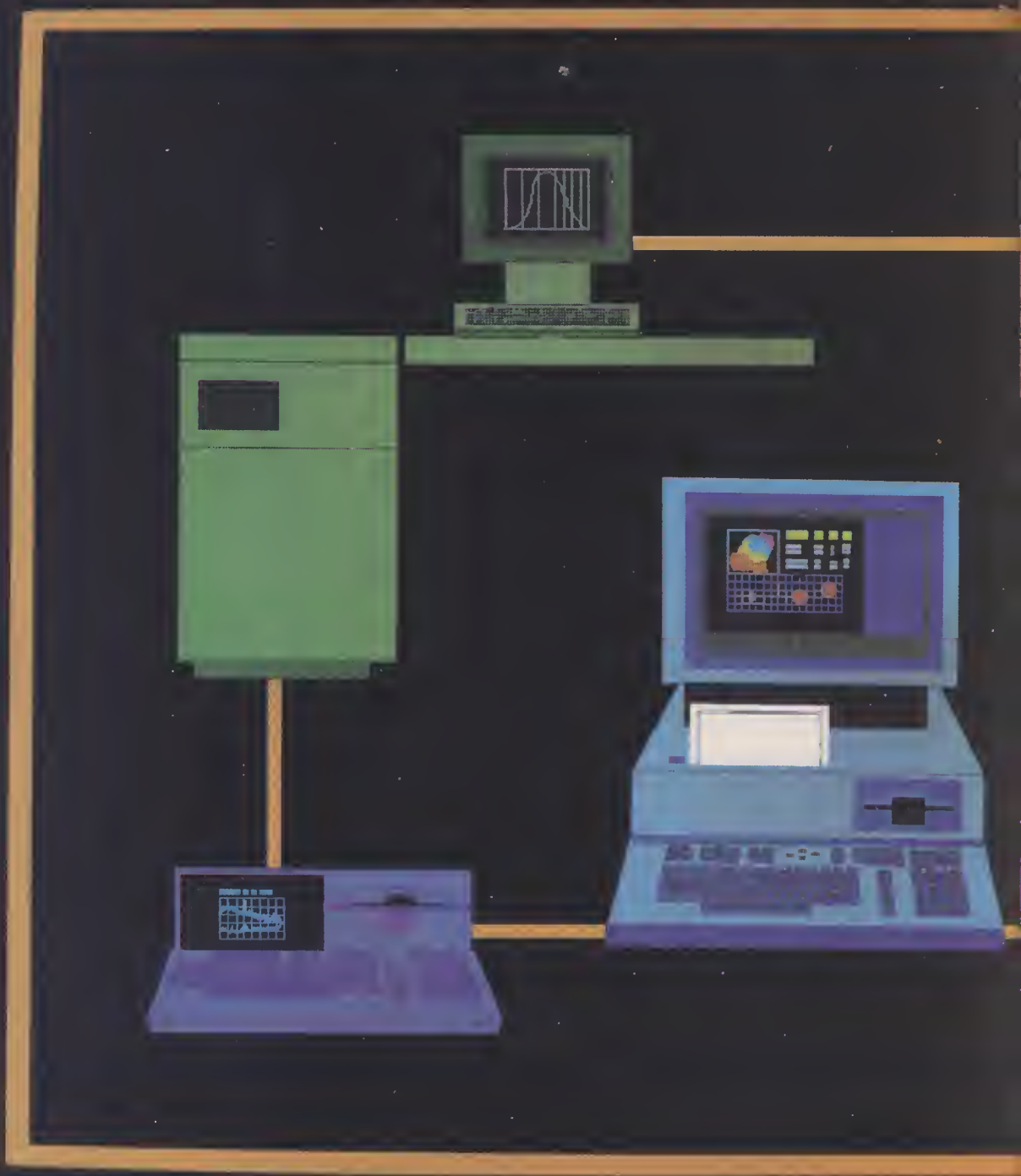
Future dilemmas. As currently practiced, sports biomechanics is unintrusive and relatively free of criticism. Using technology to analyze an athlete's performance and then working with a coach to devise training methods is far different from using steroids or other drugs to enhance performance. But biomechanics could eventually stray into controversial areas, and Dillman says sports associations will soon have to make rulings on just how far researchers can go.

"We already have the technology to put transducers into muscles and fire them from a remote site to increase the force of the muscle contraction," he says. "We could do that tomorrow. But our philosophy is that we're just trying to reach a point where we can help each athlete reach his or her own natural potential. Obviously, you can go beyond that and get into manipulation. Then Olympic competition could become a competition among scientists, not athletes. It's a problem the sports world will have to deal with."

For now, sports biomechanics depends as much on astute coaching and hard work by the athlete as on computer analysis and electronic gadgetry. And its impact is rarely immediate or stunning. "It's not something where you say, 'Hey, hold your arm a bit differently,' and the next day he holds his arm a bit differently and—bang!—there's a dramatic improvement," says walker/researcher Fenton. "So often with biomechanics, improvements come from working with an athlete over a long period." Nevertheless, he notes, a seemingly trivial change in a runner's or race walker's stride can add up over the many strides taken during a race: "It can make the difference between winning and losing." □

Dwight B. Davis is a senior editor of HIGH TECHNOLOGY.

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GALLIUM ARSENIDE CHIPS EMERGE FROM THE LAB

by Gregory Johnsen



Improved crystal-pulling methods (above) are helping GaAs chips into production to meet demands for high-speed, low-power digital circuits.

In fields such as computers, communications, and instrumentation, where performance is critical, speed means money. That's why the logical choice for future high-speed integrated circuits may be gallium arsenide, which is already achieving operating speeds up to five times that of the fastest silicon computer chips currently available. And while the fastest silicon ECL (emitter-coupled logic) circuits are nearing their projected speed/power limits, gallium arsenide (GaAs) device designers are only starting the optimization process.

There are several high-stakes markets eager to tap gallium arsenide's potential. The military needs the speed as well as the extremely high radiation resistance of GaAs chips for signal processing in missile guidance, electronic warfare, and lightweight radar systems. A commercial market is expected to develop around home TV receiving devices for 12-GHz signals from direct-broadcast satellites. This high frequency will enable small rooftop antennas to pick up the signals, but it means GaAs circuits will be needed for the mass-produced home receivers. Their radiation-resistance also makes them ideal for the communications circuitry in the satellites. And as telecommunications moves to fiber optic cables, electronic and optical processing of signals might be integrated on the same GaAs chips.

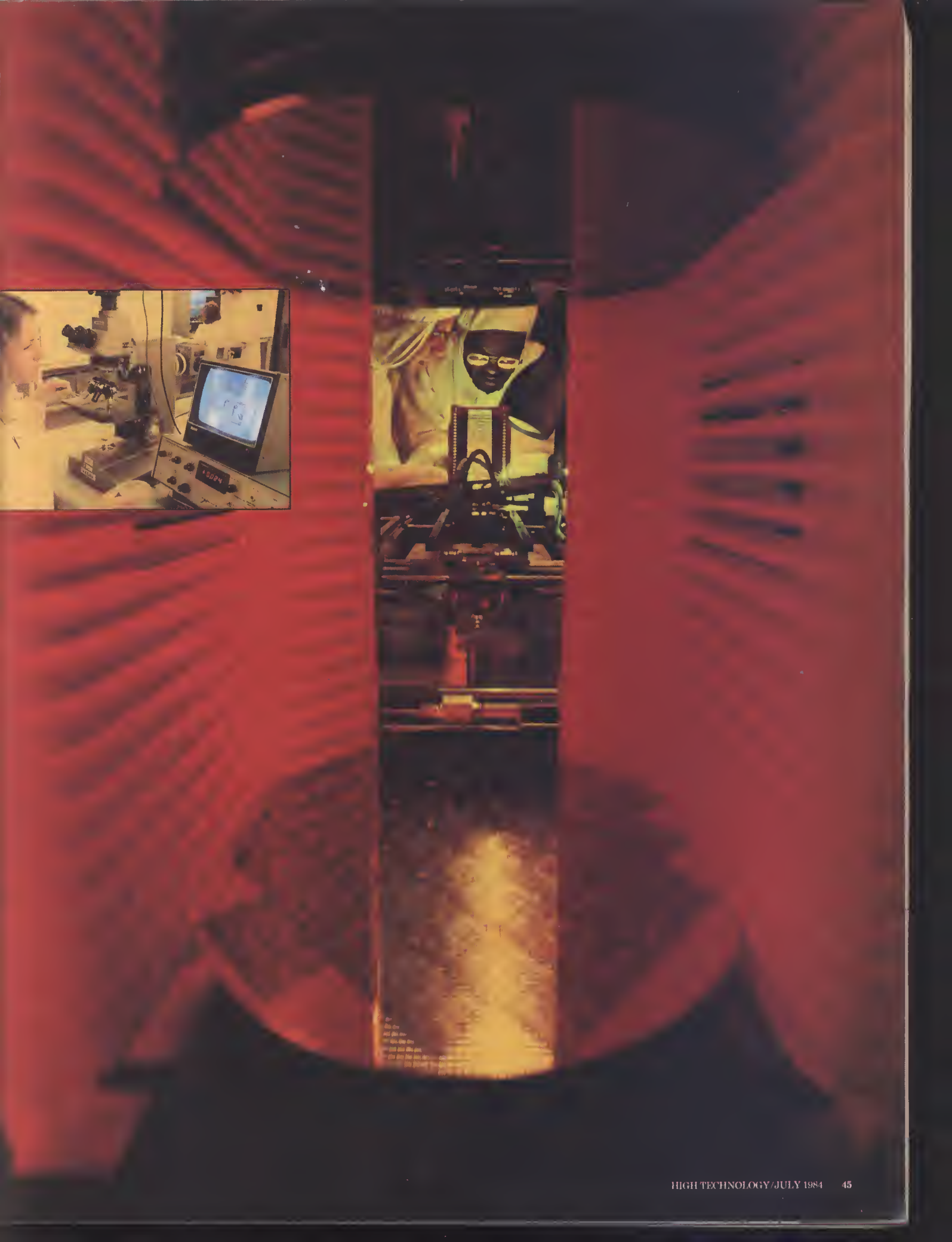
Gallium arsenide devices are not new to the microwave field; they have dominated discrete microwave component markets for about ten years. But improvements in crystal growth, doping, material deposition, and lithography have only recently made complex circuits possible. Operating at frequencies of a billion hertz and higher, microwave systems are pushing the edge of silicon's speed range; thus gallium arsenide has been essential. Silicon devices forced to operate at those frequencies would provide such weak signals that huge dish antennas would be needed—20 meters in diameter, by one estimate—while GaAs components can easily yield signals strong enough that antennas of only a couple of meters or so are adequate. Even in the early '70s, when GaAs manufacturing yields were low and the devices were expensive and clumsy to use, they were still more cost-effective than silicon-based systems requiring huge antennas.

Designers of digital systems—whether for computers, test instruments, or communications—would now like to drive circuits at similar speeds, so they too are turning to GaAs. Two companies put simple digital integrated circuits on the commercial market earlier this year. Also, random-access memories (RAMs) of 1K (1024, or 2^{10}) bits, with access speeds roughly ten times faster than those commonly available, are expected on the market by early 1985. And 4K RAMs are also on the horizon. At this year's Solid State Circuits Conference, two Japanese firms described 4K RAMs with access times of 3 billionths of a second.

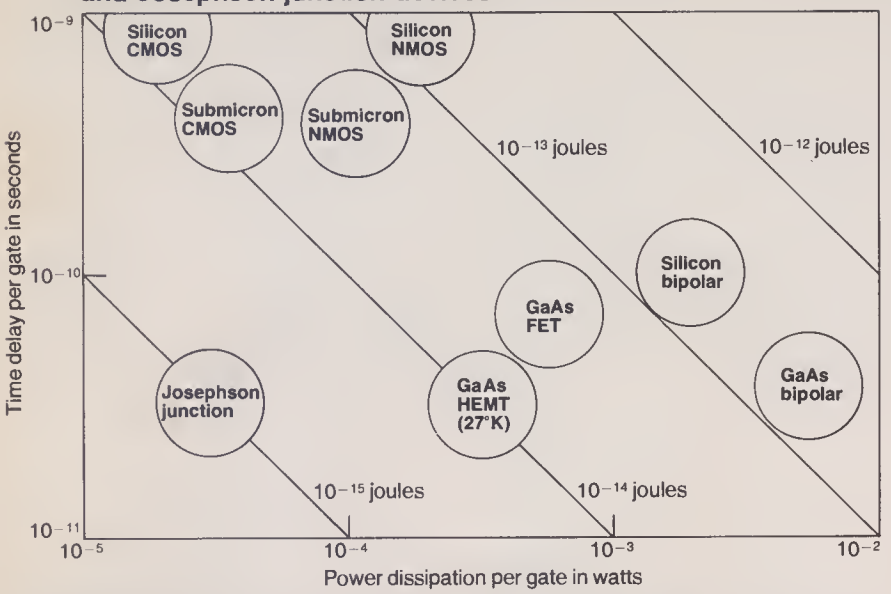
GaAs crystals' energy-band structure makes electrons light, mobile, and extremely fast. GaAs electrons have only 7% the effective mass of electrons in silicon, and their mobility at room temperature can be 8–9 times higher. In addition, if GaAs is supercooled, or if multilayer "superlattices" are employed, mobilities can be further increased another ten times or more.

Under strong, static electric fields, electrons tend to move at a limiting "saturation velocity." Because the saturation velocity for electrons in both silicon and gallium arsenide is roughly the same (about 10^7 cm/sec), proponents of silicon technology claim that their circuits will perform as well as GaAs equivalents when circuit elements are made very small. However, electrons in GaAs approach this statistical limiting velocity from much higher speeds than do electrons in silicon, and they often overshoot it: Typical electron speeds in GaAs run about 1.4×10^7 cm/sec, versus 6 or 7×10^6 cm/sec in silicon. In GaAs devices with very short

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Speed vs. power dissipation for GaAs, silicon, and Josephson junction devices



Plotting circuit speed versus power dissipation shows how chips built with different technologies compare. The diagonal lines represent constant values of power times delay—important yardsticks in microchip evaluation. As the diagram shows, silicon MOS chips are relatively slow but exhibit very low power dissipation. Silicon and GaAs bipolar chips are fast but consume a great deal of power. GaAs FETs—particularly high electron-mobility transistors built from GaAs—have excellent power-delay products only one order of magnitude higher than superfast Josephson junctions.

(micron range) line widths, this "velocity overshoot" becomes pronounced. Electron velocities of up to 5×10^7 cm/sec have been measured in some devices: It appears that GaAs maintains its performance advantage over silicon even into the submicron regime.

Furthermore, because of the difference in mobility between the two materials, silicon circuits must be driven with higher voltages to achieve saturated electron velocities. Very large-scale integrated (VLSI) circuits—chips with 100,000 or more transistors—require small voltages to minimize power dissipation and excess heat. Gallium arsenide's higher mobility makes possible saturated electron transport with electric fields about four times lower than those needed in silicon.

GaAs has other advantages besides speed and low power consumption. Intrinsic GaAs (before it is "doped" with any impurities to form circuit elements) has a high resistance to electric current; thus, starting wafers are semi-insulating, rather than semiconducting as with silicon. Such substrates simplify circuit fabrication considerably because special isolation areas, called "wells," need not be formed for each active device or transistor on the chip. Devices built in GaAs are naturally isolated by the semi-insulating substrate. One result of the elimination of wells is more compact, higher-density circuits. In addition, since the wells tend to introduce parasitic capacitance that inhibits circuit performance, GaAs chips gain an additional speed advantage.

GaAs also offers a wider range of operating temperatures than silicon and much higher radiation hardness, a decisive advantage for military and space programs. GaAs chips fabricated by standard processes can withstand temperatures from $-200°$ to $+200°$ C. Chips that operate at up to 400° C may be possible with special processes. And circuits that can withstand radiation up to 10^7–10^8 rads (versus 10^3–10^4 rads for silicon) are typical.

Indeed, the ultrahigh-performance promise of GaAs points to a booming business over the next decade. According to Strategic Inc., an industry research firm based in San Jose, Cal., the market for GaAs devices will swell from less than $100 million predicted for 1984, with almost no digital ICs, to $5.6 billion in 1992, almost half for digital chips (the rest of the market should be roughly split between analog and optoelectronic applications).

Recent activities in the industry support this optimism. Cray Research recently announced an R&D facility for gallium arsenide IC fabrication, and Tektronix (Beaverton, Ore.) opened a GaAs "foundry" to process designs executed by outside firms. At the same time, ITT started up a $2 million Gallium Arsenide Technology Center in Roanoke, Va. Other systems companies, such as Westinghouse, Hughes, and Rockwell, also have in-house efforts. Harris Microwave Semiconductor (Milpitas, Cal.) began marketing commercial integrated circuits early this year.

Meanwhile, Gigabit Logic (Newbury Park, Cal.), a start-up company dedicated to GaAs technology, opened a new $10 million facility to produce commercial high-speed GaAs chips. Initial production began during the first quarter, with medium- and small-scale integrated digital chips as the early product targets. Gigabit also recently entered into a $6.1 million R&D partnership to build four ultrafast memory chips over the next two years with a coalition of investors formed by investment banker Kidder, Peabody & Co.

In Japan, Fujitsu, NEC, Hitachi, and Mitsubishi are all developing GaAs ICs as part of a supercomputer project sponsored by Japan's Ministry of International Trade and Industry (MITI). And this government funding is only a small portion of Japan's investment in GaAs technology. Fujitsu, in particular, has stated its intentions of exploiting GaAs for supercomputers. Reportedly, it has developed 1K RAMs with 5-nanosecond access times for its own computers and those of Amdahl Corp. (Sunnyvale, Cal.), its partner in the U.S.

Britain's Plessey Research recently created a separate subsidiary to manufacture GaAs chips, and plans to spend $73 million over the next 5 years on the project. Once volume production is achieved, in 1990, the company expects sales of its GaAs chips to reach $60 million, or about 15% of its estimated available noncaptive market.

The military, a longtime supporter of GaAs IC technology, is likewise stepping up its funding to establish pilot production lines. In particular, the U.S. Department of Defense's Advanced Research Projects Agency is reported to have contracted with Rockwell and Honeywell to develop 64,000-bit high-speed GaAs memories with 10–15-nanosecond access times and a 50-MHz clock rate. The Air Force recently awarded TRW (Redondo Beach, Cal.) an $877,000 contract to develop a GaAs preprocessor for electronic warfare applications that operates at gigabit/sec data rates.

Technical obstacles. With all gallium arsenide's advantages and all the announcements, however, GaAs integrated circuits are only now coming on the market—and slowly at that. The use of GaAs for large-scale IC production is beset with technical difficulties that are only now being surmounted.

To start with, pure GaAs crystals—the type needed for IC fabrication—are

much more difficult to grow than their silicon counterparts. Only one element needs to be controlled to produce silicon crystals, whereas with GaAs, two materials must behave properly. One of those materials—arsenic—is toxic and volatile at the high temperatures needed to grow crystals.

Arsenic tends to bubble out of the high-temperature melt from which crystals are pulled. To prevent this, the crystals must be grown in an enclosure with an abundance of arsene gas. In early work, the material was grown in long silicon dioxide "boats" placed in sealed tubes to contain the arsenic.

GaAs crystals grown by this technique, called the horizontal Bridgman method, are typically D-shaped, small, and inconvenient for wafer processing. Worse, these crystals are often contaminated with silicon from the boat. They must be counterdoped with chromium, which (with oxygen) neutralizes the silicon's electrical properties to yield semi-insulating material.

Unfortunately, during subsequent wafer processing, the chromium atoms can both cancel intended device doping and redistribute themselves, causing unpredictable device behavior. The headaches of chromium redistribution can sometimes be avoided by growing epitaxial buffer films on the top of each wafer (these films follow the crystal structure of the substrate), or by limiting processing to select wafers from the heart of the ingot. Neither alternative, however, is conducive to low-cost, high-volume chip production.

The disadvantages of the horizontal Bridgman method are being overcome by adapting the ingot-growth technique used to pull silicon wafers. In this method, called the Czochralski technique, a seed crystal is dipped into the melt, then slowly turned and pulled into uniform cylindrical ingots.

The physics behind gallium arsenide's higher speed

Electrons exhibit a smaller "effective mass" in gallium arsenide than they do in other semiconductor materials like silicon. This means electrons move faster, resulting in higher-speed circuits.

The reduced effective mass of electrons in GaAs can be visualized with the use of an energy momentum diagram (left). Current flows when enough energy is applied to the material to boost electrons from the lower, nonconducting valence band to the upper conduction band. Although it takes slightly more energy to promote electrons in GaAs (1.4 electron volts versus 1.1 eV for silicon), this takes place at a point of almost zero electron momentum in the GaAs crystal.

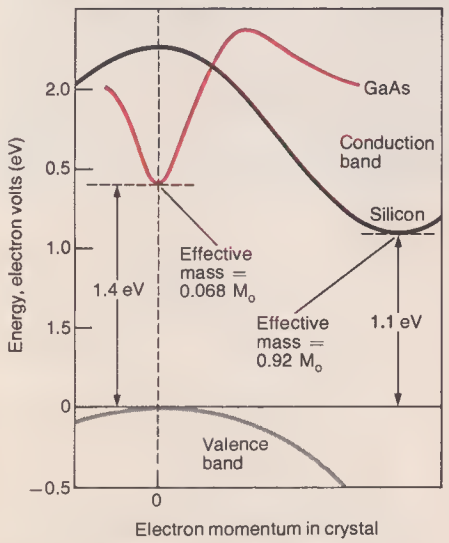
Around the zero-momentum point of silicon, in contrast, conduction-band energy is at a maximum of about 2.3 eV. Promotion of electrons to the conduction band at a higher momentum translates into a higher effective mass—the mass of an electron traveling through the crystal lattice. The effective mass of electrons in silicon is 0.97 times the actual mass, whereas in GaAs it is only 0.068.

This reduced effective mass means higher electron velocities. Plotting the mobility curves (electron velocity versus electric field) for GaAs and silicon (right) also illustrates some distinct differences between the two materials, again in favor of GaAs. Even at low electric fields, the velocity of electrons in GaAs rises very rapidly. Indeed, the electron mobility in GaAs reaches a sharp peak of 22×10^6 cm/sec at an applied electrical field of just over 3 kilovolts/cm, after which it falls and levels off to a velocity of about 10×10^6 cm/sec. This sharp peak in GaAs electron mobility is often referred to as the material's "velocity overshoot" characteristic. The velocity of electrons in silicon rises at a much slower rate, reaching about 6×10^6 cm/sec at an applied field exceeding 30 kV/cm.

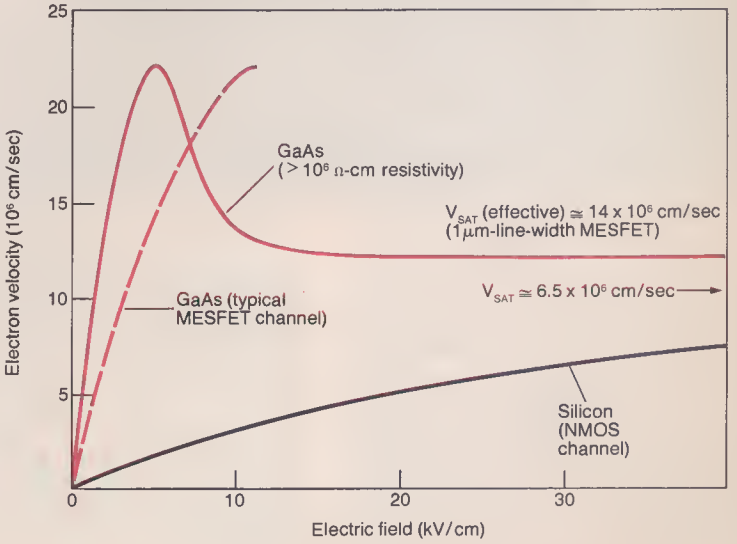
Even without velocity overshoot, the mobility of electrons in GaAs is some six times higher than in silicon, and when velocity overshoot is taken into consideration, the advantages of GaAs are even more striking. The theoretical overshoot characteristic shown by the solid curve really only applies to intrinsic (undoped) GaAs, since in doped material, electron scattering of ionized donor impurity atoms tends to limit practical mobility.

A new class of multilayer superlattice structures can take advantage of this velocity overshoot phenomenon, however. These are known variously as high-electron mobility transistors (HEMTs), modulation-doped FETs, and other names; but in each case, an undoped film of GaAs is positioned beside one or more thin films of doped GaAs containing donor electrons. Under an applied bias, the free electrons are attracted into the undoped film, where they achieve velocities of 50,000 cm/sec and higher—extremely high for a quiescent device.

Electron energy vs. momentum



Electron velocity vs. field characteristics



ALL DIAGRAMS BY MARK E. ALSOP

Two pressurized crystal-pulling techniques are now being tried for gallium arsenide wafer production: high-pressure, liquid-encapsulated Czochralski, or LEC, and an older, low-pressure method. The high-pressure method uses a floating layer of boric oxide to contain the arsenic (particularly during element reactions), whereas the low-pressure approach starts off with semicrystalline GaAs material created either through a previous reaction or through a lower-temperature reaction of arsenic vapor with a gallium melt.

Czochralski-grown GaAs materials contain many more defects than Bridgman crystals, but their cylindrical shape is more compatible with wafer-processing equipment. Czochralski wafers also allow direct device fabrication without the need for a buffer layer, dramatically reducing the cost of the starting material. Recent laboratory progress promises better crystal quality soon. Early this year, Toshiba researchers pulled an LEC crystal with a density of dislocations (imperfections in the crystal lattice) about a tenth that of other GaAs wafers—about equal to that of commercial silicon. They did it by controlling the horizontal temperature distribution in the melt 20 times more accurately than is common with other current methods. Meanwhile, researchers at Philips's Laboratoires d'Électronique et de Physique Appliquée near Paris report that they have produced crystals with dislocation densities ten times better than Toshiba's. The French have taken a different approach: They dope the crystals with impurities from the same columns of the periodic table as gallium and arsenic during fabrication.

Nonetheless, good GaAs wafers are still relatively expensive and hard to get. According to Gigabit Logic, only three of the dozens of GaAs suppliers are currently shipping 3-inch wafers (though many others have announced intentions to do so). The 3-inch wafers now sell for about $250 each, but costs of $150 per wafer are projected. In contrast, silicon wafers are up to twice the diameter (four times the area) and far less expensive. Silicon wafer suppliers are now gearing up to produce 6-inch wafers that will cost less than $30 each.

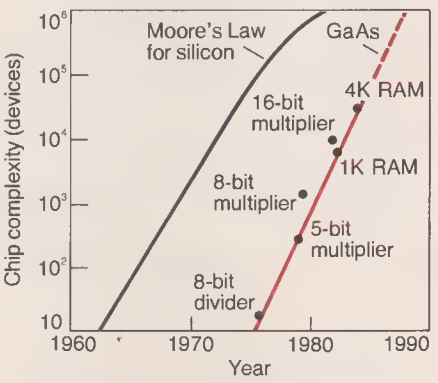
Since chips are batch-processed wafer by wafer, the bigger the wafer the more chips per wafer and, in general, the lower the cost per chip. This means that GaAs circuits cost considerably more than commodity silicon ICs, such as watch chips, dynamic RAMs, and the like. With current technology and processes, GaAs circuits are now cost-effective only for the most speed-critical applications.

But in those applications they may more than pay for themselves, according to Richard Eden, Gigabit's vice-president for research and development. Eden claims that wafer costs contribute only 15–30¢ per die to the cost of very high-performance circuits. GaAs circuits now being introduced, he says, will be competitive with state-of-the-art high-performance silicon on the basis of cost versus speed. "And in the long range," he says, "we hope to match high-performance silicon on an absolute-cost basis."

Besides the technical problems on the wafer-production side, there are also many difficulties in fabricating the transistors and other devices that must be made by the thousands on each GaAs wafer to produce IC chips.

The field-effect transistor, or FET, the basis of VLSI chips, has three terminals: source and drain electrodes and a gate that controls the current flow between them. The highest-density, lowest-power version of the FET incorporates a gate that is insulated from the rest of the transistor through a nonconducting film. With silicon, such insulating films are obtained by simply heating up the wafer in a furnace. Insulating silicon dioxide films readily grow on the surface of silicon wafers, especially in the presence of moisture. This is a primary reason that silicon is so valuable for IC production.

With GaAs, it's nearly impossible to produce thin insulating films. Neither gallium nor arsenic oxidizes with ease, let alone their complex combination.



As with silicon, the complexity of GaAs chips is increasing rapidly as time progresses. From about 1965 to 1975, the complexity of silicon chips followed a curve based on "Moore's Law" (from Gordon Moore, chairman of Intel). This states that chip complexity doubles about every year. During the '80s, as silicon chip complexity begins to flatten, the complexity of GaAs chips will still follow a steep climb because they will be able to take advantage of advanced processing technology developed for silicon ICs. At some point in the '90s, GaAs chips will contain as many transistors as silicon chips, thanks primarily to improvements in GaAs starting material. (Source: Electronics, Thomson-CSF, and Strategic Inc.)

This problem, too, has been effectively solved, however, through use of the MESFET, or metal-semiconductor FET. In this device the metal gate electrode makes direct contact with the surface of the GaAs substrate without the use of an intervening insulating film, forming what is known as a Schottky junction.

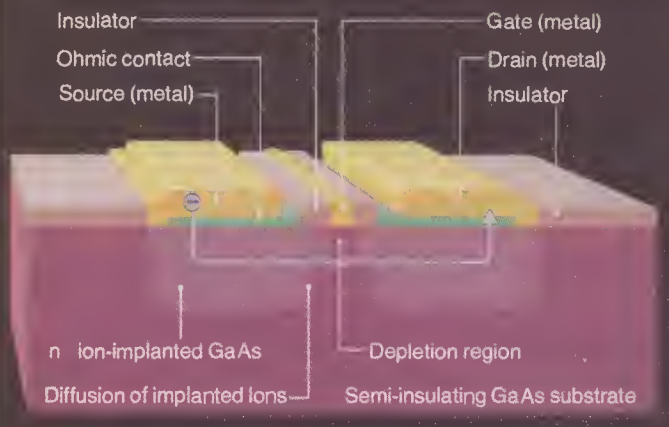
MESFETs are now the basis for practically all GaAs chips, though non-FET bipolar and even some insulated-gate approaches are in development. There are two kinds of MESFETs, the normally-on depletion type (D-MESFET) and the normally-off enhancement type (E-MESFET). Normally-on and -off refer to the transistor's conduction in the presence of zero voltage on its gate electrode. With depletion devices, a negative bias voltage must be applied to turn the device off, or halt current flow between source and drain; with enhancement devices, a positive voltage is applied to turn the device on, or initiate current flow. Both D- and E-MESFETs are now in use, sometimes in combination. GaAs D-MESFETs have been produced commercially for ten years, however, while E-MESFETs are much more difficult to manufacture and aren't yet on the commercial market.

The basic MESFET consists of a narrow metal gate electrode placed laterally between the source and drain regions. In general, two ion-implantation doping steps are used to fabricate the transistor. One is a shallow (0.10- to 0.15-micron) implant just below the gate electrode, creating a region for source-drain current called the channel. The other implantation step forms the source and drain regions, which go deeper in the bulk GaAs material. Metal contacts to the source and drain, and to the metal gate electrode, connect them to other transistors, completing the chip's functional network.

In the D-MESFET, the electrical interface created by the metal gate electrode, together with the channel doping, creates a region beneath the gate that is devoid of electrons. Beneath this depletion region, current can flow through the channel from source to drain even without a gate bias voltage, so the device is said to be normally on. The depth of the depletion region can be reduced by positive voltages on the gate or extended by negative gate voltages. This, in turn, varies current flow. A negative gate voltage may be increased up to the point where this region "pinches off" the channel, halting current flow altogether.

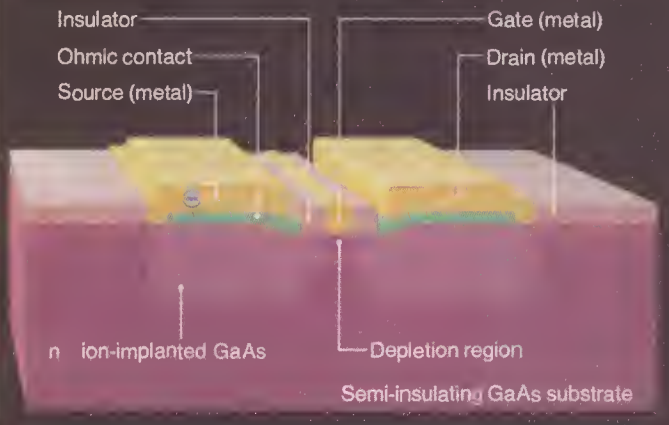
E-MESFETs are created by adjusting the depth and doping level of the channel region until it is simply pinched off

Depletion-mode FET



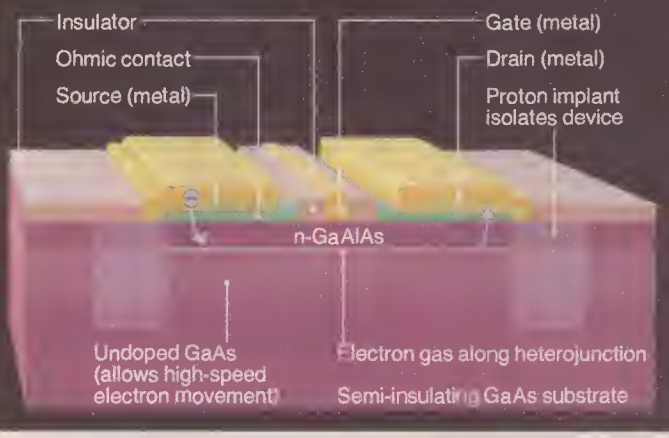
The depletion-mode, or normally-on, D-MESFET has achieved the highest level of integration because it is the easiest to fabricate. Since insulating films are not feasible on gallium arsenide, direct metal-to-semiconductor junctions are used to form field-effect transistors (MESFETs) unlike the common metal-oxide-semiconductor devices (MOSFETs) used in most silicon integrated circuits. Ion implants under the source, drain, and gate regions provide a channel for electron flow. A bias voltage applied to the metal gate creates a depletion region below it that can actually grow to the point of halting, or pinching off, current flow.

Enhancement-mode FET



Enhancement-mode MESFETs (E-MESFETs) are normally off, but conduct current with a positive gate; hence they burn less power. Unfortunately, they are hard to make. It is extrememly difficult to produce thin GaAs layers that are depleted of carriers with no applied bias, because residual charged-surface states often form. One solution, shown here, is to etch the area under the gate, though this results in a nonplanar surface.

High-electron-mobility transistor (HEMT)



The high electron-mobility transistor, or HEMT, is a structure that achieves remarkable electron mobilities and performance figures. HEMTs are also called modulation-doped FETs and two-dimensional electron-gas FETs. HEMT-type technology can be used to build both depletion-and enhancement-mode FETs; the device shown is a depletion-mode HEMT. In all cases, an extremely thin, undoped layer of GaAs is grown next to a layer with donor electrons using an advanced process called molecular-beam epitaxy (MBE). Electrons from the donor layer stream into the undoped film, where they are not slowed by collisions with dopant atoms. Mobilities in excess of 50,000 cm^2/v-sec are thus achieved.

with no applied bias. The transistor is thus normally off, and positive voltages are applied to turn it on and vary its conduction levels.

It is debatable which transistor type, the D- or the E-MESFET, is faster. But it is clear that the E-MESFET, because it is normally off, uses much less power. It is also much more difficult to produce consistently. E-MESFETs will draw excessive gate currents if the gate voltage rises above 0.7 volts, so on-chip signals must be limited to about half a volt. To consistently achieve such a small voltage swing on a complex integrated circuit means that the pinch-off voltage must be controlled to about 0.025 V. This has been exceedingly difficult to master in practice. Another problem with E-MESFETs is that surface depletion regions form between the gate and both the source and drain; these raise the source resistance and lower the transconductance and efficiency of the device. This problem may be overcome by recessing the gate region, but that complicates processing and leads to a nonplanar surface.

Being easier to fabricate, D-MESFETs have traditionally achieved higher levels of integration. An important milestone in D-MESFET technology and integration was reached about three years ago when Rockwell reported an 8-bit GaAs multiplier circuit containing over 1000 logic gates—over 6000 individual components—on a single chip. Transistor delays for the device are 150 picoseconds, resulting in a multiplication time

of 5.2 nanoseconds. By comparison, the fastest silicon multiplier, an emitter-coupled-logic unit sold by TRW, takes 70 ns to find a product, and requires more power to do so. It is only fair to add, however, that the GaAs chip, when available on a limited basis, could cost twice as much.

Recently, Japanese companies have been combining E-MESFETs and D-MESFETs on the same chip with some stunning results. The combination of E- and D-MESFETs is extremely important since a major trend in silicon integrated circuits is toward combining enhancement and depletion-mode transistors on a chip. Companies capable of mastering both E- and D-MESFET fabrication may be able to transfer important existing silicon circuitry directly into GaAs without the hassle of converting them into all-depletion-mode equivalents.

Fujitsu, for example, recently unveiled a 16-bit GaAs multiplier, which can calculate a product in just 10.5 nanoseconds. Comprising some 10,000 E- and D-MESFETs wired into 3168 logic gates, the circuit represents the level of integration possible with GaAs today. The fastest silicon multiplier, again manufactured by TRW, requires 45 ns.

The marriage of E- and D-MESFETs is particularly valuable in the design of high-speed memories. The regular structure of memory circuits leads to high density, and the normally-off transistors are necessary to contain power dissipation.

Several companies in the U.S., Japan, and Europe are developing ultrafast GaAs chips to function as computer cache memories (small high-speed memories used to speed computation). They are using a static RAM design, because its particular circuit configuration offers the easiest interfacing and the highest inherent performance.

Indeed, so far several 1K and 4K GaAs static RAMs have emerged, with data-access times ranging from 1 to 4 nanoseconds for the former and 2.8 to 3.0 nanoseconds for the latter. The fastest 1K silicon ECL RAMs also have access times below 5 ns and were first reported five years ago, but they consume ten times the power and are still not commercially available. Moreover, as the technology is perfected and circuit features are reduced, GaAs IC makers predict 1-ns to 2-ns 4K static RAMs. These will offer greater than twice the performance of the fastest silicon chips, while consuming an order of magnitude less power.

Other digital GaAs circuits being designed to perform core functions within computer arithmetic-and-logic units (ALUs) include simple gates, shift registers, counters, and adders. Like multipliers and memories, these chips perform dedicated logic functions.

In order to accommodate the remaining logical operations, a number of companies are designing gallium arsenide gate arrays, which are customized for a given application during their final processing stages. The arrays contain a matrix of logic gates, preprocessed to the point of a final gate-to-gate pattern. Different interconnection patterns can be added later, resulting in an almost limitless number of possible logical functions.

The U.S. appears to be leading the way in GaAs gate array chips. Lockheed Missiles and Space Co. (Sunnyvale, Cal.), Texas Instruments (Dallas), Rockwell's Microelectronics R&D Center (Thousand Oaks, Cal.), Honeywell, and Tektronix, all have GaAs gate array projects underway.

The state of the art is embodied in the Tektronix array, containing 1224 gates made up of nearly 7000 transistors. Using different final-metallization patterns, the firm has wired the array into a chain of logical inverters, shift registers, a serial multiplier, and a pseudo-random sequence generator.

GaAs superlattices. Respectable as the advances using GaAs MESFETs have been, researchers are developing improved structures capable of even higher performance levels. One technique that is gaining much attention involves the use of extremely thin films of GaAs alternating with films of gallium aluminum arsenide (GaAlAs). Such superlattices can actually be built using other compound semiconductor materials, but currently the most impressive results are being seen with GaAs—again, due to its high mobility.

Devices based on superlattices go by different names. Bell Labs, which applied for a patent on the technique back in 1978, calls them selectively doped heterojunction transistors, or SDHTs. Fujitsu, which has been by far the most aggressive in pushing toward the commercialization of chips based on superlattices, calls them HEMTs, which stands for high-electron-mobility transistors. Thomson-CSF uses TEGFET, for two-dimensional electron-gas FET, while at the Univ. of Illinois and Rockwell, they go by MODFET, for modulation-doped FET.

The principle used is ostensibly the same in each case. The devices, here called HEMTs, consist of a heterojunction of GaAs and GaAlAs. Whereas ordinary semiconductor junctions join oppositely doped layers (n and p) of the same material, heterojunctions join two different materials that may have the same or different dopings.

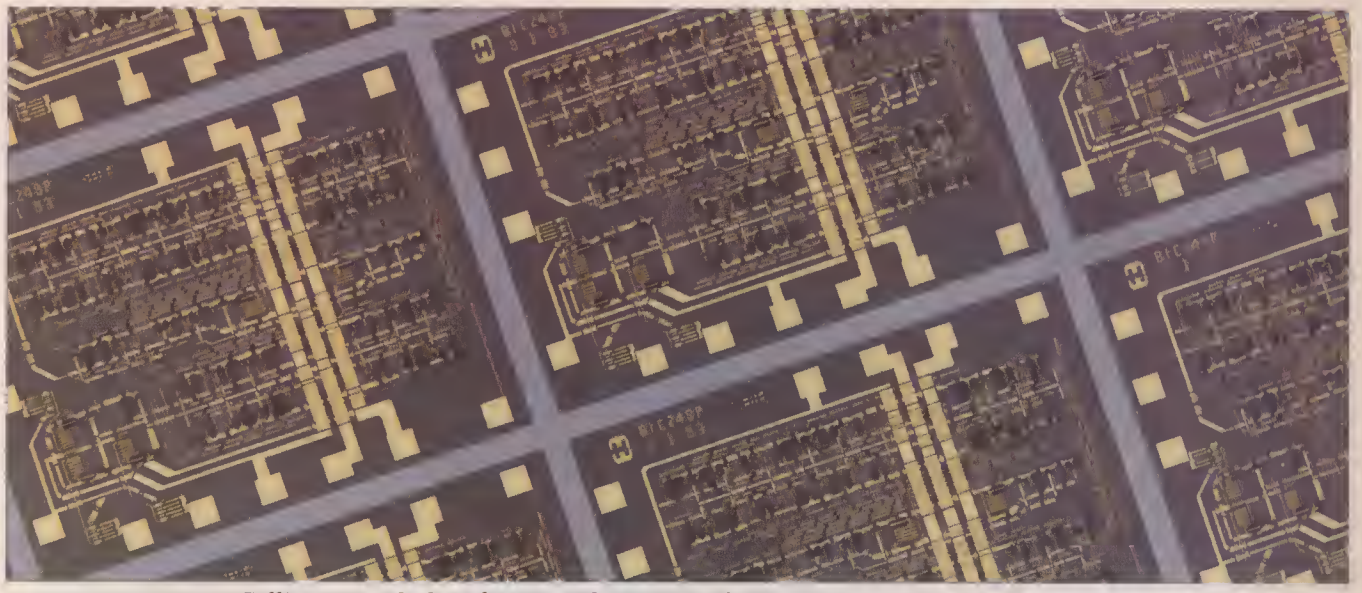
Specifically, a typical HEMT structure consists of an undoped GaAs film, an n-type GaAlAs layer, and an n-type GaAs layer, all sequentially grown on a semi-insulating GaAs substrate. The n-type layers have an abundance of electrons, but the undoped GaAs film has the highest mobility because it has no impurities to interfere with current flow. Extra electrons that pour from the GaAlAs into the undoped GaAs film have very high mobility and speed.

Fujitsu has reported system clock frequencies of as high as 8.9 gigahertz, driving narrow-line-width (0.5-micron-gate-length) HEMT circuits at liquid nitrogen temperatures (−196° C). This corresponds to a logic delay of a scant 0.022 billionths of a second (22 picoseconds) per gate, roughly three times faster than the usual MESFET structures at room temperature. (HEMTs with 1-micron gate widths and operating at room temperature have propagation delays about 25% below MESFET circuits of similar gate length, going to 50% less at liquid nitrogen temperatures.) A computer based on HEMTs, claims Fujitsu, could run with overall system clock cycles of just 2 ns—and execute over 120 million instructions per second. That's about five times the clock speed of today's fastest supercomputer.

An important hitch in HEMT production is that some of these alternating films have to be exceedingly thin—some only 30 billionths of a meter (30 nanometers) thick. As such, they can only be made using a technique called molecular-beam epitaxy, or MBE, which deposits material literally one atom at a time. MBE systems are not only expensive, however; their use for volume production levels is questionable.

Undeterred, Fujitsu and others are forging ahead with MBE-grown HEMT-like circuits, confident that suitable commercial production equipment will be developed. Initially, only simple circuits were built: ring oscillators, which loop a string of inverters back on themselves to test switching speeds, and simple frequency dividers. Fujitsu recently unveiled a subnanosecond 1K static RAM based upon HEMTs.

Integrated optoelectronics. Not only is gallium arsenide a better material for superfast circuits, it is also the material of choice for optoelectronic transceivers. When GaAs is used to build a laser diode, it produces light with a wavelength that makes efficient use of optical fibers (HIGH TECHNOLOGY, Jan. 1984, p. 43). Thus the incentive to put optoelectronic transceivers onto VLSI chips is strong. There are also programs underway to build circuits that operate directly on light beams, so that they don't have to be converted into electronic signals for process-



Gallium arsenide digital integrated circuits, such as these divider/counters from Harris Semiconductor, came onto the market earlier this year.

ing. The slower electrons would be used only to control ultraminiature light splitters, shutters, and valves that guide light beams across a chip.

Although such "photonic" circuits may be many years away, chips that integrate optoelectronic and microelectronic elements are not. Their near-term application will be primarily for concentrated telecommunication links and high-speed computer-to-computer data channels. Although discrete emitters, detectors, and fiber media exist today, present systems carry only 1340 voice conversations per fiber pair, at a data rate of about 90 megabits/sec. By 1985 they will handle 4000 conversations at 432 Mbits/sec. With integrated optoelectronic GaAs chips, 60,000 or more conversations should be possible over a single pair of fibers.

To cite one example of this work, Honeywell's Corporate Technology Center (Bloomington, Minn.) recently became the first to integrate a solid-state GaAs laser onto the same chip with FETs to drive the laser and other digital support circuitry. Besides the laser, which resides in an etched well, the chip contains much of the control and driving electronics, including the FET driver, two buffers, a multiplexer, and a counter, all requiring over 150 transistors.

After a laser and all transmission electronics have been integrated onto the same GaAs chip, the next challenge will be to add a photodiode detector and receiving circuitry for a complete, monolithic optoelectronic transceiver. Rockwell is planning just that, and more. It plans to surround complete silicon subsystems with several of these transceivers, resulting in an optical "crossbar" switch capable of being interconnected to similar systems through duplex optical links operating at data rates of 1.4 billion hertz. The resulting network of ultranodes would have tremendous processing prowess.

Yet despite these ambitious plans, two- or three-chip approaches with separate lasers, detectors, and driving circuits are expected to be the workhorses for carrying fiber optic communication in the near future.

Analog circuits. Digital and lower-frequency analog GaAs chips are built with many of the same components—transistors, resistors, capacitors, etc.—whereas monolithic microwave integrated circuits (MMICs) require rather exotic processing techniques that may be quite different. At these higher microwave frequencies, it is often necessary to include circuit elements such as high-frequency inductors, transmission lines, and techniques to form air bridges for interconnection between elements.

Lower-frequency analog GaAs circuits are typically used for front-end amplification and filtering in radio and television transceiver subsystems. A typical outdoor direct-broadcast satellite receiver, for instance, uses a low-noise amplifier, a bandpass filter, a mixer, a local oscillator, an intermediate-frequency amplifier, and a power converter. Late last year Toshiba reported such a system on just two GaAs MMICs. A single monolithic GaAs satellite receiver cannot be far off.

In defense systems the big push in analog GaAs is for a monolithic transmit/receive module for phased-array radar systems. The phased-array antenna, which can supplant awkward mechanical antennas for directing radar beams, relies on a large two-dimensional array of transmit/receive modules. The phase of the microwaves fed to each module is adjusted electronically to arrive at a set of desired relationships among radiating elements. Varying the relationships varies the direction of the radiated beam without the need for mechanical parts.

In its simplest form, a transmit/receive module for an element of a phased-array radar requires many elements: a power amplifier, a low-noise amplifier, an electronic switch, and a phase shifter. Government subcontractors are on the verge of integrating all of these components onto a single GaAs MMIC. Future variations could add oscillators, multipliers, mixers, power dividers, and other components, further reducing production costs.

Many other bright opportunities also exist for analog-type GaAs chips. Large markets could develop for the impending boom in mobile cellular communications and for marine radio hardware.

As large as its market may become, GaAs will certainly not replace silicon in applications where very high speed is not required. Silicon's lower materials costs and somewhat simpler processing will likely always give it the price edge. But as GaAs wafer prices fall and integration levels rise, gallium arsenide will find a steadily widening niche in the market. □

Gregory Johnsen is a West Coast consultant who specializes in high-speed integrated circuit technology.

For further information see **BUSINESS OUTLOOK** *on next page and* **RESOURCES** *on page 78.*

BUSINESS OUTLOOK

Gallium arsenide vendors look to the future

Despite glowing projections for the growth of gallium arsenide integrated circuits, these high-speed/low-power-consuming chips will not significantly affect the market for silicon devices until well into the next century. By 1992, annual GaAs sales may amount to only $5.6 billion, in contrast to a projected $79 billion for silicon sales, according to Strategic Inc. (Palo Alto, Cal.), a market research firm.

At a time when silicon suppliers are lowering prices while increasing the versatility of their products, GaAs chips—selling for three to five times the price of their fastest silicon equivalents—are limited primarily to applications in which power and speed requirements warrant the added cost. Last year more than 70% of those applications were in the military; within eight years, however, commercial applications could account for as much as 79% of sales, according to Strategic.

"Although minuscule compared with the silicon IC market now, gallium arsenide IC's are expected to grow to approximately 3% of the market within the next ten years, with major new applications in computers, fiber optics, and microwave communications."

Richard W. Soshea
VP and General Manager
Harris Microwave Semiconductor

The GaAs market in 1983 was valued at approximately $48 million. Analog chips (amplifiers, modulators, multiplexers, and converters) accounted for 75%; digital chips (memory, registers, CPUs, gate arrays, and random logic ICs) had a 14% share; and optoelectronic chips (line drivers, repeaters, and receivers) captured the remainder. By '92, reports Strategic, digital sales will account for 47% of the projected gallium arsenide market; analog, 28%; and optoelectronic, 25%.

Although commercial applications are expected to spur growth at a fast-clipped 56% annual rate between '87 and '92, most of the more than 40 domestic GaAs IC suppliers are now targeting their products either for the defense market segment or for in-house research applications. Exceptions include Harris Microwave Semiconductor (Milpitas, Cal.) and Gigabit Logic (Newbury Park, Cal.). Earlier this year both companies announced the first of what they say will be families of digital GaAs ICs intended for use in telecommunications, test instrumentation, and computing.



Soshea Eden

Communications and instrumentation applications are expected to provide the biggest revenues in the commercial sector over the next several years. Strategic predicts that chips designed for fiber optic and satellite communications systems will earn suppliers $10 million in revenues this year, $82 million in '87, and more than $1 billion in '92. Chips used in high-frequency instruments (semiconductor test equipment or seismic signal processors) could earn revenues of $8 million in '84, $86 million in '87, and $1.1 billion in '92.

Consumer and computer applications are also expected to drive commercial sales. Chips designed for devices such as televisions that receive broadcast signals directly from satellites are projected to reach $4 million this year, $63 million in '87, and $756 million in '92. Chips used in supercomputers and voice recognition systems could generate $6 million worth of revenues in '84, $56 million in '87, and $865 million in '92.

Without more involvement in the commercial GaAs sector, U.S. companies stand to lose valuable market shares to Japanese suppliers, contends Yves Blanchard, VP of Strategic's semiconductor group. These include Fujitsu, Nippon Electric, Sony, and Sanyo. "Firms concentrating on the merchant market are already moving down the learning curve and cutting prices through economies of large-scale production," notes Blanchard. "Down the road, U.S. GaAs IC suppliers may find themselves competing at a severe cost disadvantage."

But some analysts assert that U.S. suppliers can concentrate on military applications now without hurting their future chances for success. "GaAs is just too expensive to justify using today in applications in which silicon can do the job," notes Doug Sparks, VP of international marketing for Gnostic Concepts (Menlo Park, Cal.). He adds, however, that suppliers can still go through the learning curve by meeting military demands for high-speed circuits in communications and weaponry systems. Among the larger companies whose GaAs involvement centers on defense are Raytheon, TRW, Hughes, Rockwell, Lockheed, and McDonnell Douglas.

"Rather than simply replace silicon in existing high performance products, gallium arsenide digital integrated circuits will provide entirely new opportunities for advanced ultrahigh-speed systems."

Richard C. Eden
VP, R&D
GigaBit Logic

Other firms, best known for their standing within the computer industry, are working with GaAs circuits in their labs. These firms may be positioning themselves to enter the commercial sector once it takes off, according to Tom Holland, an analyst with Dataquest (Cupertino, Cal.). They include Cray Research, Tektronix, Bell Labs, Honeywell, and Hewlett-Packard. "There's more activity in this market than meets the eye," says Holland. "The U.S. has a lot of companies with a foot in the door."—*F.J.C.*



JEFFREY MAYER

From the pulsating rhythms of disco to the funky syncopations of keyboardist Herbie Hancock to the hypnotic soundtrack of *Chariots of Fire,* electronic music has joined the mainstream of popular culture. Until recently, computer-based synthesizers were so expensive ($15,000–$40,000) that only well-heeled professional musicians could afford them. Over the past three years, however, the marriage of microcomputers and music has given rise to a number of software-based systems costing less than $2000 that convert popular personal computers into versatile music machines. The advent of these "soft instruments" is transforming the musical instrument industry. Says Robert Moog, father of the keyboard synthesizer, "I think we're on the threshold of seeing computer-based home music systems replacing the piano as something that young children learn music on."

Microcomputer music systems are based on a simple but ingenious concept: interfacing a musical keyboard and a set of digital oscillators to a personal computer and letting software control the sounds. While conventional synthesizers use hardwired oscillator circuits, most software-driven music

MAKING MUSIC WITH MICROS

New software packages can convert personal computers into home music systems, tools for music education, or full-fledged synthesizers

by Jonathan B. Tucker

systems produce sound waves by scanning lists of numbers stored in memory. Musical parameters are displayed on the video monitor and can be changed by entering a few numbers or letters on the computer keyboard. Not only do these systems play music like conventional keyboard instruments, but they can generate a virtually limitless variety of tone colors, or timbres.

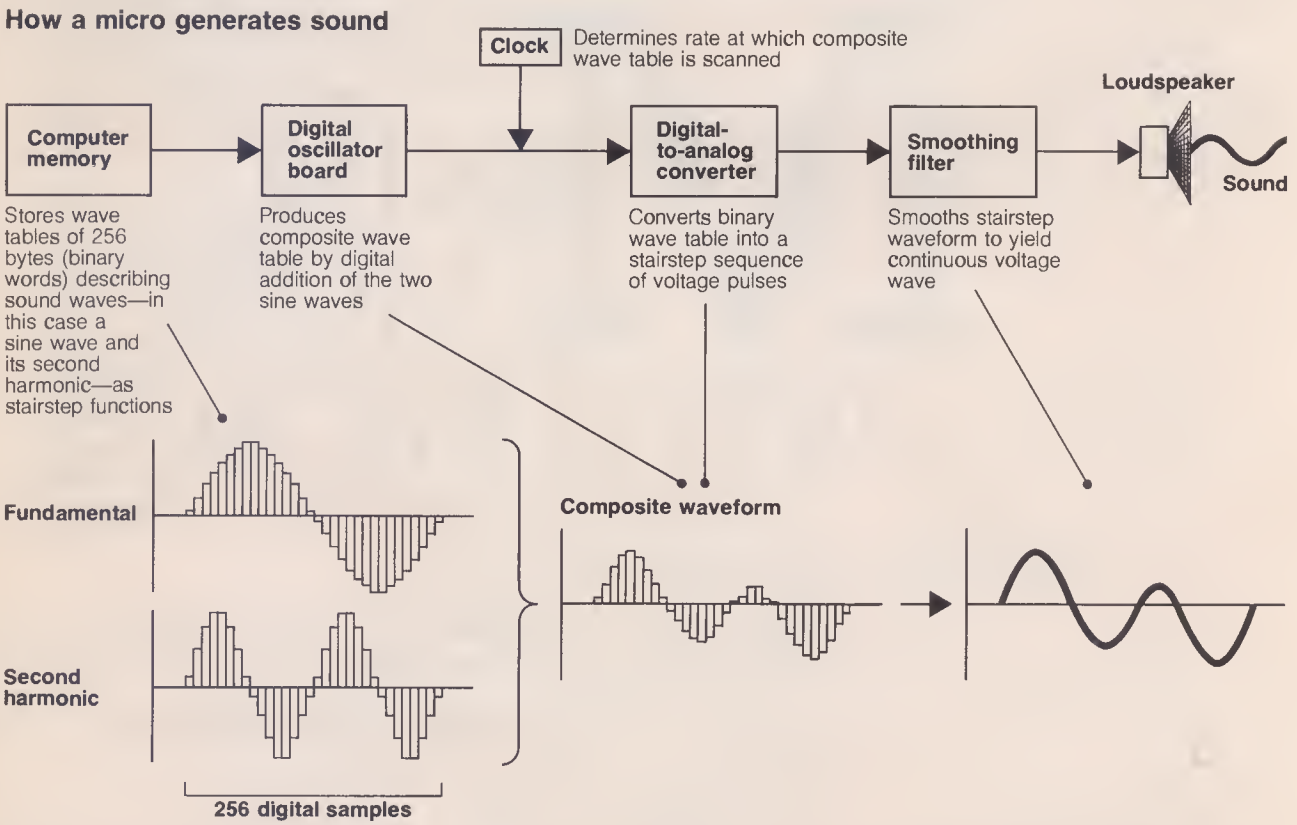
Applications of computer music systems can be divided into three areas: professional, educational, and home entertainment. Interest in electronic music is growing among professional musicians, particularly in rock and jazz-fusion. In addition to producing strange and wonderful sounds, computer music systems can store complex sequences of music for later playback on command, providing a repetitive background such as a bass line. A musician can play multipart compositions into the computer, edit and mix them electronically, use a transcription program to convert the sounds to musical notation, and print out a hard copy of the finished score. Composers can create new pieces and hear them immediately, instead of waiting weeks or even years for a live ensemble to perform them.

The precise time control provided by these systems also makes them ideal for radio programs, ads, and movie and video soundtracks. "With a computer music system, you don't have to hire musicians and you don't need a recording studio," says Paul D. Lehrman, a musician and computer programmer in Cambridge, Mass. "You watch the videotape, work out your cues, and play the soundtrack into the computer. You can play it back for the client at any time and make changes by modifying the stored sequence until you get it right. Then you lay down the finished soundtrack right on the videotape."

Computer music systems are finding extensive applications in music education as well. Elementary music-education software teaches the basic concepts of sound and rhythm by correlating tones with graphic displays on the computer screen. Intermediate-level programs teach harmony and composition, and train the ear to recognize pitches and chords; advanced programs facilitate experimentation with new sounds, scales, and styles of composition.

Computer music systems are also entering the home-entertainment market. Because of the flexibility, small size, and low cost of software-based music systems, some industry analysts believe that they will replace the home organ and eventually challenge the ubiquitous home piano. Although there are currently only about a dozen companies producing music-related software, Larry Green, executive vice-president of Empire Sales & Marketing (Boston), predicts that the field will more than double in size over the next year. "The music store of the near future will have computers, computer-interfaceable keyboards, digital recording equipment, and programmable drum machines," he adds.

Sound synthesis. How does a microcomputer make music? It starts by synthesizing sound waves. Sound consists of a series of air-pressure vibrations, which are converted by the inner ear into nerve impulses that the brain interprets as sounds. The perceived pitch of a musical tone is determined by the frequency at which the sound wave fluctuates (measured in cycles per second, or hertz), while the



Micros make music by scanning through wave tables—sequences of binary numbers stored in memory. These numbers are passed to a digital oscillator board, which combines the basic waveforms into more complex waveforms through a process called additive synthesis. The digital representation of a composite waveform is then sent to a digital-to-analog converter, which translates it into a sequence of voltage pulses. This stairstep waveform passes through a filter to yield a smooth voltage wave that can drive a loudspeaker.

DIAGRAMS BY M. ALSOP/D. HANNUM

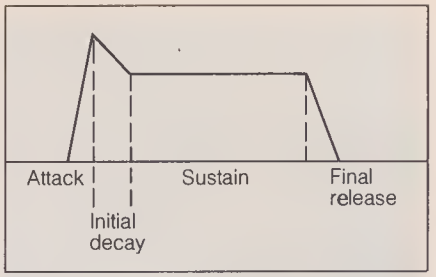
loudness of the tone is directly related to the amplitude of the wave. The human ear is sensitive to a narrow band of frequencies ranging from about 20 to 20,000 hertz. (Hearing acuity declines with age; the typical 30-year-old male can only hear up to about 15,000 hertz.)

Since digital computers work with discrete signals—pulses of positive and negative voltage that represent a binary code of 1s and 0s—they must model continuous sound waves with a stream of binary numbers. The simplest digital synthesizers use fixed waveforms to produce tones of different frequencies, but have a buzzy, kazoolike sound. In contrast, software-driven synthesizers can generate a virtually unlimited variety of waveforms, and hence are better suited to making music.

A microcomputer such as an Apple II represents a sound wave mathematically in the form of a wave table: typically a set of 256 binary numbers corresponding to the amplitudes of closely spaced points along one cycle of the repeating waveform. Each point is encoded by an 8-bit binary number (a binary word, or byte), such as 00110011. The wave table is stored on a floppy disk, from which it is loaded into the computer's random-access memory (RAM). The computer then scans the list of numbers many times a second, generating a continuous stream of 8-bit words that describes the periodic waveform.

Converting this stream of binary numbers into sound requires an additional piece of hardware: an integrated-circuit board containing one or more digital-to-analog converters (DACs). A DAC can be thought of as a programmable power supply whose output voltage is determined by a binary-number input. As the microcomputer scans through the wave table stored in its memory, it transmits 8-bit words in rapid sequence. All eight bits are sent out simultaneously through a parallel connector, and travel to the DAC along the separate wires of a ribbon cable. As each 8-bit word is fed into the DAC, it is immediately translated into the corresponding analog voltage signal. For example, the binary word 00000001 might yield an output of .01 volt, 00000010 an output of .02 volt, 00000011 an output of .03 volt, and so on. Thus the DAC converts the sequence of binary words sent by the computer into a continous voltage wave.

Because the microcomputer's sampling rate is finite, the voltage wave emanating from the DAC is actually a stairstep approximation of the desired smooth waveform, the width of each step being one 256th of a cycle. This stepped waveform is smoothed by passing through an electronic circuit called a filter. Finally, the smoothed voltage wave is amplified and used to drive a loudspeaker.



An amplitude envelope describes how the loudness of a note changes over time, an important factor in simulating different instruments. Microcomputer music systems define the envelope with four parameters: attack time, initial decay time, sustain level, and final release time.

The simplest audio waveform, consisting of vibrations at a single frequency, is called a sine wave, because it follows the trigonometric sine function. A sine wave produces a very pure tone, like that of a flute played softly in its middle register, but it quickly becomes monotonous to listen to. Most musical sounds are composites of several frequencies, called harmonics. Generally the lowest harmonic (the fundamental) is predominant and determines the apparent pitch of the sound as a whole.

The other harmonics are multiples of the fundamental: The second harmonic is twice the frequency of the fundamental, the third three times, and so forth. An instrument's timbre is determined mainly by the relative strengths of the harmonics. By adding harmonics to a sine wave in the digital domain and then feeding the composite waveform into the DAC (a technique known as additive synthesis), a microcomputer can generate composite waveforms with distinctive timbres that roughly simulate different instruments. For example, a triangle wave, consisting of the fundamental frequency plus odd-numbered harmonics with declining amplitudes, has a clarinetlike timbre.

Although the wave's shape is determined by the wave table, its frequency (pitch) is determined by the rate at which the computer scans the wave table and sends the stream of binary numbers to the DAC. For example, if the scanning rate is 1000 times a second, the voltage wave emanating from the DAC—and hence the audio tone produced by the speaker—will be at 1000 hertz. Doubling the scanning rate produces a tone an octave higher.

Although it is possible to specify almost any periodic waveform with a 256-word wave table and convert it into sound with a DAC, the sampling rate imposes an upper limit on the frequency that can be reproduced. According to the Nyquist Theorem—the basis of all digital audio theory—a computer must generate at least $2n$ digital samples (binary words) per second to reproduce a tone with a frequency of n hertz. Because there is no lower frequency limit, however, a microcomputer can generate any low-pitched tone without difficulty.

In addition to timbre and pitch, each musical tone has an amplitude envelope that specifies how its loudness changes over time. On practically every instrument, a note takes a finite amount of time to build up to its full amplitude (attack time). The tone then dies away partially (decay time), levels off to an average amplitude (sustain level), and finally dies away to silence (release time). An acoustic instrument has a characteristic envelope that, like its timbre, sets it apart from other instruments. For example, a guitar produces tones that rapidly rise and fall in amplitude, whereas a flute's tones have a longer attack time and can be sustained. Digital synthesizers generate simple envelopes in accordance with the four basic parameters—attack, decay, sustain, and release.

Soft instruments. Music software is currently available for a number of 8-bit personal computers based on the 6502 microprocessor, such as the Apple II (and IIe), the Commodore 64, and TRS-80 Models III and 4. There are two types of computer music systems: delayed-playback and real-time. In the former, notes are entered into the computer one at a time by typing in numbers and letters representing pitch, timing, and phrasing. The user edits the composition on the screen and then instructs the computer to "play" the piece or store it on a floppy disk.

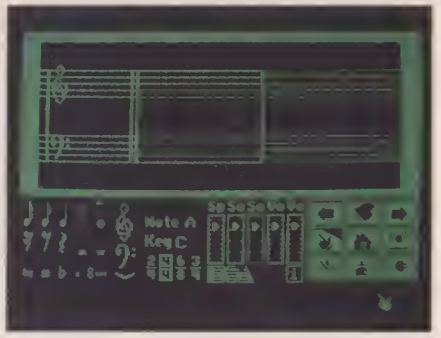
For instance, the $565 Compu-Music system, made by Roland (Los Angeles), consists of a small module containing a digital music synthesizer that generates piano, bass guitar, and drum sounds. This module can be connected to a personal computer (Apple II, TRS-80, NEC PC-6000, or IBM PC) and, for audio, to any amplifier or stereo system. Software enables one to compose music by instructing the computer which notes to play, their duration, and the timing between them; the piece can be played back at any time. Compu-Music is difficult to use, however. "Trying to remember all the codes is really hard," says musician/programmer Lehrman. "You can sit there for hours trying to figure out what to do."

A number of other inexpensive music-software packages for personal computers have recently entered the market. Commodore, Texas Instruments, Atari, Tandy/Radio Shack, Apple, and

several software companies offer programs costing about $40 that enable personal computer owners to compose short pieces or listen to prerecorded works stored on disks; simple graphics routines provide a simultaneous display of piano keys or musical notation.

An example is "Music Construction Set" (Electronic Arts, San Mateo, Cal.), a program for the Apple II and the Commodore 64. The software costs $40 but requires a $100 Mockingboard digital oscillator card (Sweet Micro Systems, Providence, R.I.), which improves the quality of the Apple sounds. A joystick controls a movable hand on the video screen that picks up notes, sharps and flats, clef signs, and other musical symbols and places them on two staves (sets of five horizontal lines). The computer will store a composition on disk and play it back at any time; the user can also change volume, tempo, and key during playback. Although the program is designed for teaching composition, experienced musicians may also find it useful.

Another innovative software package, DX-1 ($239) from Decillionix (Sunnyvale, Cal.), enables a microcomputer to make digital recordings of real sounds, a feature that until recently was available only on expensive dedicated synthesizers. The Decillionix program requires a special circuit card (consisting of several analog-to-digital and digital-to-analog converters) that fits into the back of the Apple; a microphone then plugs into a jack on the card. Using the microphone, one can record any live sound (such as drums or voice) and store it in digital form in the computer's memory or on floppy disk. Because the stored sounds can be addressed by the computer, one can then play them back by pressing certain letters on the computer keyboard. Speeding up or slowing down the playback rate changes the pitch.



Music Construction Set, made by Electronic Arts, is a $40 composition program for the Apple II. A joystick controls a movable on-screen hand that picks up notes, sharps and flats, and other musical symbols, and sets them down on a staff. As many as 1400 symbols can be displayed on two staves, including chords of up to six notes. The computer will play back the music at any time.

Real-time systems. Adding a musical keyboard, interface cards, and special software converts a personal computer into an electronic synthesizer that can be played in real time, much like a home organ. Two real-time systems currently on the market are designed for use with the Apple II: the alphaSyntauri, made by Syntauri (San Mateo, Cal.), and the Soundchaser, made by Passport Designs (Half Moon Bay, Cal.). The alphaSyntauri and Soundchaser are roughly comparable, although they differ in certain design details. Both include a four- or five-octave musical keyboard, an interface card that connects the keyboard to the computer, digital oscillator boards, a pair of foot pedals for special effects, and a library of software on floppy disks. For Apple owners, the alphaSyntauri and the Soundchaser each cost $1495, about the same as a fairly inexpensive home piano. Together with the computer, monitor, disk drive, and dot-matrix printer, the price comes to



Two real-time micro music systems are on the market: alphaSyntauri (below) and Soundchaser MX-5 (right). Both are software-driven systems based on the Apple II personal computer. They include a digital oscillator board, keyboard, and other accessories. Although the instruments are played like a home organ, they offer much greater flexibility.

roughly $4000, still less than many home organs.

These micro-based systems generate sounds with inexpensive digital oscillator cards that plug into peripheral slots inside the Apple. Analog output is sent via one or more jacks to a stereo system, an instrument amplifier, or a pair of headphones. The alphaSyntauri uses the MusicSystem digital oscillator board, manufactured by Mountain Computer (Scotts Valley, Cal.); Passport Designs' Soundchaser system uses an oscillator board of the company's own design. Last month Sequential Circuits (San Jose, Cal.) introduced a six-voice board costing less than $300 that plugs into one of the expansion slots on the IBM PC or the Apple.

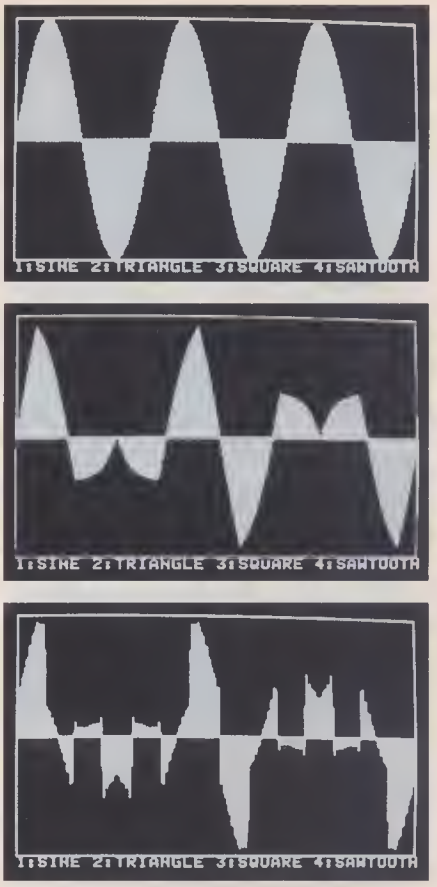
While high-priced digital synthesizers use multiple DACs, the MusicSystem board generates several voices with one DAC by a technique known as time-division multiplexing. A typical 8-bit microcomputer contains a clock with a frequency of approximately 1 million hertz. Because this clock is many times faster than any audio frequency, it can be divided into 16 separate cycles, or "logical oscillators," which are fully programmable and can be addressed separately. Since each clock cycle has a sampling rate of 32,250 hertz, the maximum frequency output per oscillator is, by virtue of the Nyquist Theorem, about 16,125 hertz.

The alphaSyntauri comes with floppy disks offering a wide variety of simulated instruments called "presets." Each preset specifies two oscillator voices—with different waveforms and amplitude envelopes—which are routed through separate audio outputs to simulate stereo. A typical preset file might include simulations of such instruments as a pipe organ, trumpet, flute, oboe, saxophone, clarinet, strings, cello, guitar, and electric piano. Between five and 10 master files, each containing 10 presets, can be stored on a single floppy disk.

In order to play the alphaSyntauri, one inserts a floppy disk into the Apple disk drive and loads a master file containing 10 presets into the computer's random-access memory (RAM). The video screen then displays the menu of 10 instruments. By pressing a number on the Apple keyboard (0–9), one can activate any of these presets, much like setting the stops on an organ. To change presets, one simply types a different number. As an instrument is selected, the video screen displays its name and envelope parameters. With a few keystrokes, one can then set attack, decay, sustain, and release times over a range of 256 gradations.

The alphaSyntauri is polyphonic, meaning that it can play chords of up to 8 notes at a time using any preset instrument stored in memory. A microprocessor in the musical keyboard scans the keys thousands of times a second. Upon encountering a depressed key, it tells the computer to generate a tone of the appropriate pitch by scanning the wave table at the corresponding frequency. Because the keyboard information is updated many times a second, the delay between striking a key and the onset of a note is not perceptible.

The alphaSyntauri keyboard is also sensitive to the speed at which each key is struck, enabling the player to vary loudness somewhat for greater expressivity. Under each key are two switches, one activated when the key is partway down and the other when it is fully depressed. The computer measures the time interval between activation of the two switches, calculates the velocity, and adjusts the amplitude (loudness) of the output signal accordingly. Unfortunately, the alphaSyntauri uses an inexpensive keyboard (about $300) that is inconsistent in interpreting velocity information; striking the same key 20 times with the same amount of force yields several different volume levels.



New types of sounds can be created on micro-based music systems by additive synthesis. Syntauri's Wave program digitally adds two different waveforms and their harmonics to produce a composite waveform, which is displayed on the computer screen. Here a sine wave at the third harmonic (top) is combined with a triangle wave at the fifth harmonic to yield a composite waveform (middle). This waveform is then added to a square wave at the seventh harmonic to obtain an even more complex result (bottom).

Making waves. Because the micro-based systems are controlled entirely by software, the musician is no longer limited by the dials and switches on a dedicated synthesizer. By loading a new group of presets, he can continually give the instrument new identities. In addition to the preset sounds that come with the synthesizer, special programs (including Syntauri's Wave and Quickwave programs and Passport Designs' Wavemaker) enable the player to design new waveforms by additive synthesis—combining waves of different frequencies into composite waveforms that are richer and more complex.

With the Wavemaker program, the user lists the harmonics desired by typing in numbers on the computer keyboard. The computer then sums the waves corresponding to these harmonics and displays a graph of the composite wave on the screen. This composite waveform does not have to contain a complete harmonic series; it might include only the first five harmonics, only odd-numbered harmonics (first, third, fifth, seventh, etc.), or harmonics of different amplitudes. Finally, the user can further refine the shape of the waveform by manipulating game paddles (rotatable knobs) to move a cursor around the screen.

Although the alphaSyntauri and the Soundchaser can produce a wide variety of interesting sounds, they have a number of hardware limitations. The digital oscillator boards in these systems, says Moog, "do a great deal for what they cost but are not of the quality of an analog instrument in the same price range. The quality of the sounds is limited by the resolution of the waveform, the clock speed, and the degree of filtering after digital-to-analog conversion. If you try to produce a complex waveform at a high pitch, there is so much distortion that the tone comes out sounding like noise."

Microcomputer-based music systems also have software limitations. For one thing, they use only additive synthesis, neglecting other powerful methods such as frequency modulation. Moreover, since the waveforms and envelopes are derived from scanning fixed wave tables, they do not vary over time within a note or change as a function of pitch or amplitude. In contrast, acoustic instruments generate highly dy-

Herbie Hancock: micro music pioneer



JEFFREY MAYER

Jazz-fusion recording star Herbie Hancock, 44, has been in the vanguard of bringing microcomputer technology into the world of popular music. He started out in classical music, beginning piano lessons at age five and performing Mozart with the Chicago Symphony Orchestra at 11. At Grinnell College in Iowa, Hancock majored in engineering for two years and then switched to music. After graduation, he played jazz piano with Coleman Hawkins, Donald Byrd, and Miles Davis before starting his own group in 1968. Since then he has made nearly 50 albums, as well as film scores for *Blowup* and *Death Wish*. Recently he won a Grammy Award for the song "Rockit" from his latest album, *Future Shock,* and composed the score for the film *A Soldier's Story*.

Electronic music was a natural outgrowth of Hancock's interest in engineering and in new jazz forms. He discovered synthesizers in 1971 and played one on his 1973 *Headhunters* album. Six years later he was introduced to the musical potential of microcomputers by his keyboard engineer, Bryan Bell. "When I first got my Apple," Hancock remembers, "I was recording over at United Western Recording Studios. Bryan was in the maintenance room, writing a program that described the patching of the instruments I had—which ones were patched into which effects, and which voices went where." (Patching is the combination of oscillators to create specific sounds; this process was done manually with patch cords on early synthesizers but now is done electronically.)

Hancock owns two software-based synthesizers, the alphaSyntauri and the Rhodes Chroma. "The alphaSyntauri actually utilizes the Apple as the source of the sounds, while the Chroma uses the Apple to store musical sequences," he says. "On my last album, *Future Shock,* I used the alphaSyntauri along with another instrument to play some of the melodies and countermelodies." Hancock uses the alphaSyntauri for composing as well. Its 16-track recording software stores the notes as he plays, so he does not have to pause and write them down.

Bryan Bell has also developed a micro-based system for controlling a variety of instruments from a few master keyboards. Hancock often plays 10 to 20 different synthesizers in one song to achieve a variety of effects. "I used to have to run around from instrument to instrument, which was sort of ridiculous," he says. "What I wanted was to be able to access the electronics of any of the synthesizers from two stationary keyboards, one for each hand, and a portable keyboard that I could wear around my neck." Bell solved this problem by building an automated patch bay—a box connected to the Apple so that sounds on different synthesizers can be selected by typing commands on the computer keyboard.

With this system, Hancock says, "I can look at the menu on the screen and indicate which instruments I want to be the controllers and which ones I'd like to patch them into. I give it a setup routine in the beginning, and then any time in the middle of a song I can change the patching of any of the instruments." Hancock can even program the computer in advance to change the patches at a specified point. "For example, I can tell the Apple that on the second chorus it should switch automatically from the instrument I've been playing to one or two other instruments," he says. Bell is currently upgrading the patch bay so that it can be controlled in real time by pushing single keys ("macro commands") on the Apple keyboard.

Hancock is also delving into MIDI, the new hardware/software specification system that enables electronic instruments equipped with a standard digital interface to communicate with one another and with micros. Last winter he bought two MIDI-equipped synthesizers: a Yamaha DX-7 and a Memory-Moog plus. Eventually the interfaces will enable him to control up to eight MIDI instruments from a master keyboard and to store multitrack musical sequences on the Apple. But Hancock points out that although most of the newer electronic instruments on the market have the MIDI interface, older ones do not. "I can't trade in an Arp Odyssey for a new MIDI version," he says, "because the Arp company doesn't exist anymore. I suppose I could hire someone to find a way to convert it to MIDI, but that would cost a lot of money. That's where my automated patch bay comes in. I'm converting MIDI to something my patch bay can understand, so that it can control all my instruments."

Overall, Hancock is very impressed with the capabilities of micro-based synthesizers. "I think that microcomputer instruments like the alphaSyntauri have an incredible amount of flexibility," he says. "The only synthesizer I own that has comparable flexibility is the Fairlight CMI, which costs $30,000." Moreover, he feels that what micro-based systems lack in sound quality they make up for in price. "You can't expect an instrument that costs so little to sound as good as a dedicated synthesizer that costs considerably more," he says. "The fact that you can get a digital synthesizer at that price is already unbelievable."

Hancock is looking forward to the day when micro-based instruments are capable of top-quality music synthesis. "My needs are not the same as someone who's making music at home or on a semipro level," he says. "But I'm sure that in the future these instruments will have a line that is up to professional standards, yet with the same low prices."

To completely satisfy musicians like Hancock, micro-based synthesizers will need longer keyboards with better volume control, as well as sound-generating systems that offer a wider range of frequencies. The sound quality of current micro-based synthesizers is constrained by the use of inexpensive oscillator boards and the relative slowness of the Apple II's 6502 microprocessor, which limits the digital sampling rate. Hancock suggests that an improved instrument might utilize the Macintosh processor, which is about 15 times faster, or a special-purpose system for multitasking or coprocessing. In any case, he is convinced that micro-based synthesizers will eventually achieve a sound quality approaching that of digital recording. "It's a digital instrument," he says, "so why not?"

namic waveforms in which harmonics rise and fall at different rates within a note and vary markedly at different pitches and amplitudes. Furthermore, noise, such as the rasping of a violin bow against the strings, plays an important role in producing the characteristic timbres of acoustic instruments.

Because of the simplicity of the sound-generating process, micro-based music systems cannot imitate acoustic instruments realistically, although they can produce a wide variety of satisfying timbres. Dedicated computer-based synthesizers such as the Synclavier II, made by New England Digital (White Water Junction, Vt.), or the CMI, made by Fairlight (Rushcutter's Bay, N.S.W., Australia), offer considerably better sound quality, but at more than 10 times the cost.

The alphaSyntauri is capable of several special effects. Vibrato—a rapid fluctuation in pitch characteristic of wind and string instruments—can be added in the digital domain by modulating the primary waveform with a second, lower-frequency waveform. Game paddles that come with the Apple computer control the rate and frequency range of the vibrato. The rate can range from less than 1 hertz for a sirenlike effect to about 20 hertz. Other effects include glide (sweeping smoothly from one note to the next along the frequency scale), controlled with a foot pedal, and pitch bending (altering the pitch of a note up or down to achieve an effect reminiscent of an electric guitar), controlled with game paddles.

A feature called Ensemble activates up to 8 different instruments (16 oscillators) with one keystroke, making the sound "thicker" and more interesting. (Because there are a total of 16 oscillators, the use of Ensemble reduces the number of notes that can be played at once.) One can also play two or more instruments at a time by "splitting" the keyboard; the lower two octaves of the keyboard might be set for bass guitar, and the upper three octaves reserved for string voices.

Both the alphaSyntauri and the Soundchaser can be synchronized with an electronic percussion machine, creating a rhythmic background for keyboard playing. This feature is particularly useful because percussion sounds are difficult to reproduce on a software-based synthesizer. The reason is that many percussion sounds consist of "white noise"—a random distribution of frequencies throughout the audible spectrum. Although a white-noise waveform can be generated from a random-number table, the frequency restrictions of the oscillator boards limit the quality of the audio output.

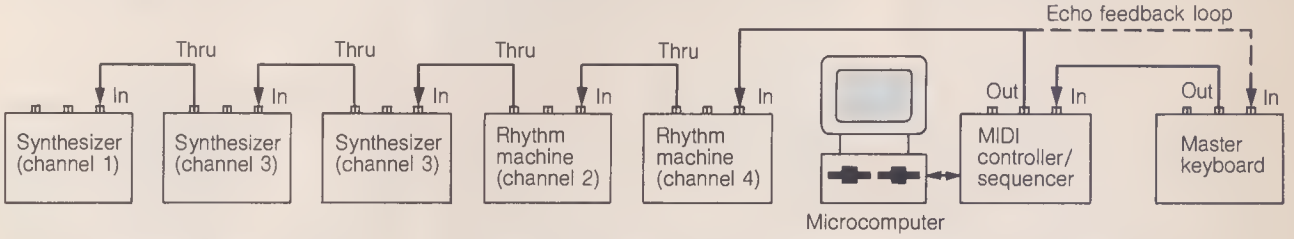
Recording and transcribing. Both Syntauri and Passport Designs offer software operating systems—called respectively Metatrak II and Turbo-Traks—that convert a personal computer into a simulated 16-track recording studio. A basic component of these programs is a sequencer, which records exactly what is played on the keyboard and then plays the piece back immediately or records it on disk for later playback. Each note in the sequence is stored in the form of 8 binary words specifying pitch, amplitude, timing, etc.

Because the sequencer program has 16 separate tracks, a musician can orchestrate a multipart musical arrangement by layering instrument parts on top of those previously recorded. He plays the first part on the musical keyboard using one preset instrument, types in a new preset number to switch instruments, and instructs the computer to play back the first part while simultaneously recording the second. This overdubbing process can be repeated until 16 different parts have been recorded. During playback, one can alter any parameter of the sound (including vibrato, envelope, volume, and tempo), turn individual tracks on or off, and change the orchestration by keeping the same note files but using a different set of instruments. Moreover, any part can be automatically transposed up or down a four-octave span.

The software recording interface simulates useful features of a multitrack tape recorder, including erase and fast forward. The Syntauri program includes punch-in and punch-out editing, which enables one to replace short segments of a track without having to rerecord the entire part. A sync-to-tape option also allows every track in a Metatrak or Turbo-Traks recording to be transferred individually to a multitrack tape deck in perfect synchrony.

A current limitation of the sequencer programs is storage. The capacity of Passport Designs' Turbo-Traks depends on the amount of memory in the Apple computer. A 48K RAM chip stores 4000 notes, a 64K RAM chip about 8000. Syntauri's Metatrak II stores only about 3000 notes—the equivalent of a 4-minute pop song—and even less if key-velocity information is included. But a hardware and software option called Metaextender, released in May, includes a 256K memory card with a capacity of 20,000 notes.

Transcription software is also available for converting stored note sequences into musical notation, which can then be displayed on the computer screen or printed out as a hard-copy score. Composer's Assistant ($179), a program from Syntauri, first asks the user to supply basic parameters such as



Musical Instrument Digital Interface (MIDI), a hardware/software system, enables several electronic instruments (such as synthesizers or rhythm machines) to be controlled from a single master keyboard. As many as eight instruments can be organized in a daisy-chain configuration. Digital data from the master keyboard pass through a microcomputer-linked controller, which allows the micro to store and play back MIDI information. The data trains, labeled with binary channel numbers, are then fed over a single bus to the "slave" instruments, which can be set to different channels. When the master keyboard is played on a specific channel, only those instruments set to the same channel will sound. In addition, each instrument copies all the MIDI information and passes it along to the next instrument in the chain. There is no detectable lag between instruments as long as relatively small amounts of data are being fed over the network (such as a bass line, timing information for drum machines, or keyboard rhythm accompaniment) or if just a few instruments are exchanging large amounts of data (such as multiple runs of notes or quick chord progressions).

time and key signatures and tempo. The program analyzes the stored note file, accurately measures rhythm and note duration, and follows a complex set of rules and procedures to format the score on a single or double staff. The composer can edit the score on the screen before producing hard copies on a dot-matrix printer.

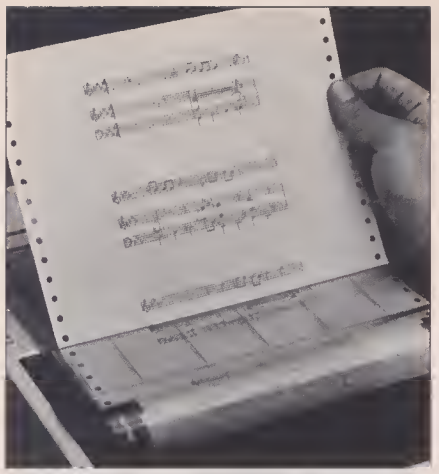
The ability of the transcription program to combine 16 tracks of music into one piano score with bass and treble lines, and to transpose any line immediately, makes it ideal for producing studio session parts. Says Lehrman, "If I'm doing a string arrangement for a studio recording session, I can work out the string parts on the computer, print out each part separately, and hand them out to the musicians."

The transcription program has some limitations, however. Although it does a good job of transcribing keyboard pieces that are accurately performed, it does not correct for playing errors such as rushing or hesitating. The length of the printed score is also limited by the amount of music that can be stored in memory. Moreover, the output of the Composer's Assistant is rather crude-looking: eighth and sixteenth notes in series are printed with separate stem flags instead of a continuous beam, and all stems point up.

Recently, Passport Designs released a more sophisticated transcription program called Polywriter ($299), which handles a wide variety of formats, including scores for piano, chorus, or orchestra. The program does an elegant job of notation, including such features as proper direction of note stems and flags, ties, triplet brackets, rests, and nine-note chords. The score can then be printed out on a dot-matrix printer at a speed of 2 pages a minute.

Digital interface. A recent advance in computer music has been the collaboration of three leading manufacturers of electronic instruments—Yamaha (Buena Park, Cal.), Roland, and Sequential Circuits—to develop standard digital hardware and software so that electronic instruments can communicate with one another and with microcomputers. Called the Musical Instrument Digital Interface (MIDI), this system is now available on a number of new electronic instruments.

MIDI is an informal agreement on interface circuitry and the "grammar" of a standard, nonproprietary language for sending meaningful digital information between electronic instruments. Instruments equipped with MIDI can transmit digitally encoded information telling other MIDI instruments linked to them when to sound and what notes



Printout of the Polywriter music transcription program demonstrates the impressive quality of the notation. A microcomputer generated the score automatically from a stored file of music that had been played earlier on the Soundchaser keyboard. (The score in the photo is the song "As Time Goes By.")

to play. "A MIDI device is a source of information, a sink of information, or both," explains Steve Haflich, a lecturer in music at MIT. Physically, MIDI appears as two or three jacks on an instrument for receiving, sending, or passing along MIDI data. To simplify the interconnection of instruments, MIDI data are carried over standard audio cable and are transmitted in a serial, bidirectional stream at a rate of 32,250 bits per second.

MIDI offers two important benefits to musicians. First, as MIDI-compatible equipment is introduced, players will be able to purchase keyboards, sequencers, and rhythm units from a variety of manufacturers with the assurance that these units will work together as an integrated system. Playing a MIDI synthesizer linked to another MIDI instrument causes the first synthesizer to sound the notes and, simultaneously, to send a stream of digital information representing notes played, note durations, volume levels, and other data over the audio cable.

MIDI has multiple channels to which different instruments can be assigned. Data sent out by each instrument are labeled with a 4-bit channel number. Thus a MIDI synthesizer linked to the master keyboard and set to the same channel will pick up the data stream and respond to it. For example, notes played on one MIDI instrument can sound on another, two MIDI instruments can produce different sounds in response to the same stream of notes, and rhythms set up on a keyboard can be played on a drum machine. Roland recently introduced an electric guitar equipped with a MIDI interface; hooked up to a synthesizer playing in "slave mode," the guitar sounds like an organ, xylophone, or some other instrument.

The other main benefit of MIDI is that it can enable a microcomputer to control a set of stand-alone synthesizers. A few hardware/software packages for connecting MIDI instruments to a host microcomputer are currently available. Passport Designs makes MIDI interface cards ($195) for the Apple II and the Commodore 64, and Roland recently introduced the MPU-401 MIDI Processing Unit ($175)—a "smart" interface for the Apple, IBM PC, and PCjr. The MPU-401 functions as a data recorder, looking after all aspects of storing and playing MIDI data except the host computer's memory management. It therefore increases the speed and efficiency with which MIDI data can be processed.

Although MIDI has a wide variety of potential applications, nearly all the software presently available is for storage of sounds and sequences. Recording from multiple synthesizers is possible because of MIDI's channel-select capability, in which separate channel codes are assigned to data from different instruments. Passport Designs' MIDI/4 ($99) is a four-channel recording program that enables a personal computer to record multiple tracks from four MIDI instruments (one track at a time) and has a capacity of 7000 notes. Each track is stored in memory by playing the instrument live to a computer-generated metronome beat. The recorded tracks are then combined to form a complete musical piece, which can be played back on either the original instruments or different ones. Roland's MIDI Music Recorder software ($100) can store multitrack sequences from up to eight electronic instruments, but has a capacity of only 3500 notes.

A third digital recording program, Sequential Circuits' Sequencer 64 ($195), is designed for the Commodore 64 and any MIDI-equipped synthesizer. "Our audience is musicians, and since we knew they would have to go out and buy a computer, we chose the Commodore because at $200 it's very affordable," explains Steve Salyer, Sequential Circuits' marketing manager. Resembling a plastic game cartridge, the Sequencer 64 plugs into the game slot on the Commodore and comes with all software stored in read-only memory (ROM) and a capacity of 4000 notes. Using this device, a musician can record eight different sequences of variable length, each containing up to six tracks and including velocity information and pitch bending. Once the phrases have been recorded, they can be linked in any order to create a composition. The piece can then be edited, transposed, speeded up, slowed down, or synchronized with a drum machine.



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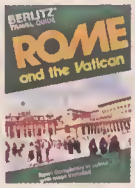
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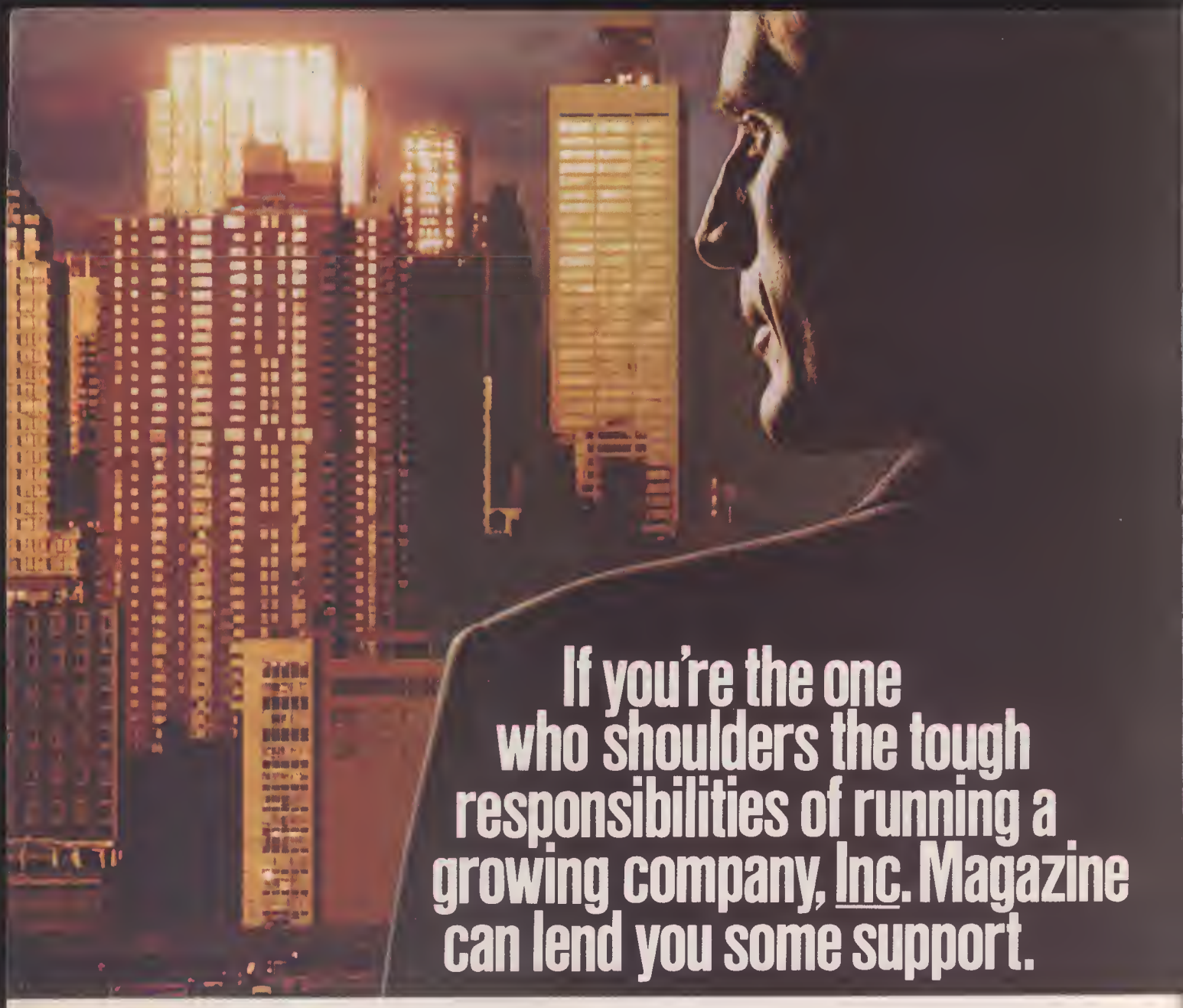
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"For another $200, a user can buy a disk drive, so he can put together any number of songs and then dump them to disk," Salyer adds.

MIDI recording software offers musicians powerful capabilities for performing and recording. "Say you're a keyboard player fortunate enough to have several MIDI-equipped synthesizers," says Steve Leonard, a Los Angeles–based musician and programmer. "If you've got a personal computer with a MIDI unit and 8-track recording software, you can prerecord all your parts except the one or two that you're actually going to play on stage. So in concert or in the recording studio, you set up your racks of synthesizers, load up the computer with the prerecorded tracks, and hit the RETURN key. The computer then spits out all the prerecorded parts, so each synthesizer is playing a different part in real time." In this way, MIDI enables a single performer to play several instruments at once, with the computer serving as "conductor."

Since MIDI is a serial device (that is, it transmits one bit at a time), some critics have questioned whether the interface is fast enough to handle 8 channels of MIDI data simultaneously. Roland claims that its MIDI code can transmit over 500 notes a second; according to MIT's Haflich, this resolution is adequate as long as each instrument is playing a fairly simple part. "Normally, for notes of a chord to be perceived as simultaneous, you're talking about a few hundredths of a second, which is the equivalent of a few tens of MIDI note-event transitions," he says. "So the speed of the interface is on the order of what you need."

MIDI offers a wide variety of potential applications, including multikeyboard orchestration, composing and editing of sequences, automated music notation and transcription, and integration of video synthesis with music synthesis. The average musician who uses a personal computer to control his MIDI instruments will probably not do much in the way of programming; instead he will be more likely to buy pre-written software for manipulating, storing, or transcribing MIDI information. A MIDI version of Passport Designs' Polywriter transcription program is already available, and a number of companies (including Passport Designs, Yamaha, Roland, and Sequential Circuits) are working on MIDI editing programs that should be reaching the market in the next few years. Communications programs are also being developed for transmitting MIDI data over telephone lines through a modem, so that a musician in New York will be able to "phone" a piece of electronic music to a studio session in Los Angeles.



PHOTO BY MARK THAYER/EQUIPMENT COURTESY OF WURLITZER CO

Guitar controller from Roland is equipped with MIDI. It can therefore be interfaced with a synthesizer, giving it access to a wide variety of timbres, ranging from xylophone to trumpet.

But Leonard contends that although MIDI has a lot of potential, the major manufacturers are not putting much of an effort into making it a viable product, because of the expense of developing sophisticated software. "They've essentially provided the input and output plugs and some basic software, and if you want to do anything sexier than that, you have to do it yourself or find someone to do it for you," he says. Richard King, an engineer at Roland, responds that the company is releasing the programming specifications for the MPU-401 to anyone who requests them, in order to encourage software development. "I would say that there's a great interest among independent programmers right now in developing MIDI software," he adds. Unfortunately, very few people have really mastered both music and programming and are willing to invest the hundreds of hours required to develop a top-notch product. As a result, it will be some time before the new programs are musically literate and able to get the most out of the equipment.

Most early applications of MIDI will be aimed at the professional and semi-pro market, but as the cost of stand-alone synthesizers comes down, there will be a growing demand for programs for the home-entertainment market. Roland's King believes that a major future application of MIDI will be for music education. "If teacher and student both have an Apple and a MIDI electric piano, the teacher can record technical exercises or duets on the system and have the student take the disk home and practice with it." Chris Albano, vice-president for marketing at Passport Designs, says his company is developing prerecorded MIDI albums, as well as programs for teaching chords, intervals, jazz, and pop music.

Although microcomputer-based music systems are still at an early stage of development, they are evolving rapidly. Current systems may lack the sound quality of top-of-the-line dedicated synthesizers, but they are nonetheless capable of generating a remarkable variety of timbres at a fraction of the cost. Moreover, because microcomputer music systems are modular with respect to both hardware and software, they will be able to incorporate advances in music-generation and electronics technology without rendering the main components obsolete. Says Moog, "The strength of these systems is that they are open-ended. Once you buy the basic hardware, updates and extensions of the system are very cheap."

In addition to providing powerful new capabilities for musicians, the computer music revolution promises to bring the pleasures of music making to people who would like to play and compose but who lack basic performing skills. "The computer allows you to use your intellect as your talent," says Chris Noyes, an instructor at Berklee College of Music (Boston). "You need to have musical ideas, but you don't have to be a proficient keyboard player. If you hear something that you like and can play it slowly, one note at a time, you can create a very complex composition. And because the computer serves as a score pad, you don't have to spend two years learning notation." For those of us who abandoned music lessons in childhood, then, computer music systems offer a second chance. □

Jonathan B. Tucker is a senior editor of HIGH TECHNOLOGY.

For futher information see **BUSINESS OUTLOOK** *on next page and* **RESOURCES** *on page 78.*

BUSINESS OUTLOOK

Home users drive music software sales

The emerging music software market is small but loaded with potential. Once consisting only of high-end professional packages for computer-based synthesizers at $40,000 or more, the market now includes entertainment and educational programs that run on reasonably priced home computers.

"Our studies indicate that more than 30% of all home computer owners are interested in using their systems for musical applications," says Bill Moulton, chairman of Waveform, a music software supplier in Berkeley, Cal. "We had a choice of going after the limited professional market or the huge, untapped home market. The choice wasn't difficult."

Approximately 7 million homes are now equipped with personal computers, and Bill Ablondi, an analyst with Future Computing (Richardson, Tex.) projects the number could swell to 48 million by 1988.

Analysts say that it's still too early for accurate projections on the size of the music software market. Rather than list music software as a separate category, most research firms group such packages under entertainment or education.

More than $405 million worth of home entertainment software will be sold by year's end, and $650 million by 1988, according to Mary Ellen Dick, an analyst with Software Access (Mountain View, Cal.). The education software market should generate $207 million worth of home sales this year and $356 million by '88. While both markets are experiencing high growth, Dick says that the music software segment will grow even faster than education and entertainment overall. "Parents would rather spend their money on software that combines education and entertainment features," she explains. "The dual functionality of music packages will add significantly to their market appeal."

Such optimism is forcing even the pioneers in the computer music industry to reorient their strategies toward the nonprofessional. Syntauri (San Mateo, Cal.), whose flagship product, alphaSyntauri, is used primarily by professional musicians such as keyboardist Herbie Hancock and guitarist Steve Morse, recently broadened its product line with hardware and software for amateurs and the musically illiterate.



Fedor



Moulton

"Computer music systems are hybrid products that appeal to traditional buyers of pianos and organs as well as to computer enthusiasts. We think the market could easily grow to $200 million by 1987."

Allan J. Fedor
President
Syntauri

"Music software is unique in that it bridges several different markets. It's a productivity tool for the professional, an educational tool for the student, and an entertainment tool for everyone."

Bill Moulton
Chairman
Waveform

"We had been neglecting the casual home enthusiast in favor of the professional," admits Wade Bray, Syntauri's product manager. "We finally realized, however, that the consumer market is by far the most lucrative." Although Syntauri just unveiled its new low-end products, Bray says the company is already experiencing considerable growth. He adds that Syntauri will continue to address the professional market but that the bulk of the company's new products will be consumer-oriented.

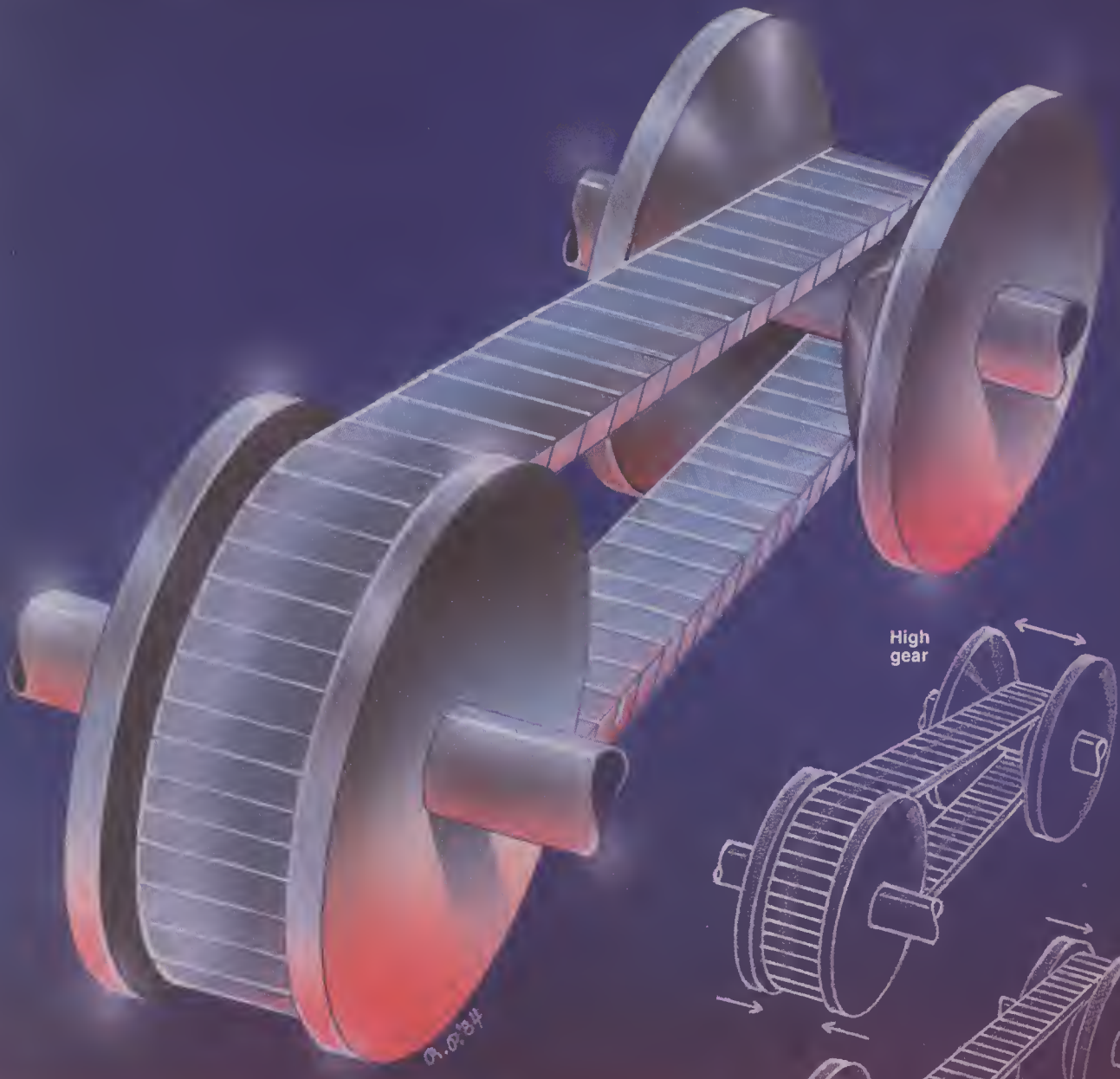
Computer music programs are available from more than 15 third-party software vendors as well as from personal computer suppliers such as Apple, Commodore, Atari, Canon, Nippon, and Sharp. Priced at $40 to $50, those programs may run "as is" on home systems or may be enhanced with special keyboards or music synthesis circuit boards.

MusiCalc from Waveform is priced at $49.95 and is available with a professional keyboard for $249 or a special beginner's keyboard for around $79. The program now runs only on the Commodore 64 computer, but Waveform plans to tailor it to IBM and Apple systems as well.

Rather than sell just software, Syntauri is taking the systems approach. The company's low-end offering—called Musicland—sells for $495, runs on Apple II computers, and includes touchpad, joystick, synthesizer board, and software. While that program is aimed at children, Syntauri also offers a package—Simply Music—designed for use by beginners and advanced musicians alike. Including software, keyboard, synthesizer board, and foot pedal, that system sells for $1495.

Most music software suppliers are getting their products to customers through a variety of distribution routes. Syntauri sells its packages not only in authorized Apple dealerships but also in musical instrument stores and in stereo and component video outlets. MusiCalc is being sold in computer specialty stores as well as through mass merchandisers. The program was the top-selling software product in both Sears and Montgomery Ward stores during its first months on the market.

Besides Syntauri's and Waveform's packages, other music software programs on the market include Synthesound from Human Engineered Software (Brisbane, Cal.), Song Writer from Scarborough Systems (Tarrytown, N.J.), Fun With Music from Epyx (Sunnyvale, Cal.), and Music Construction Set from Electronic Arts (San Mateo, Cal.).—***F.J.C.***



by Ernest Raia

CONTINUOUSLY VARIABLE TRANSMISSIONS

Gearless power trains get set for a comeback to help automakers boost fuel economy

ROBERT PASTERNAK

Impressive gains have been achieved in automobile fuel efficiency over the past decade—mostly by making cars smaller and lighter. Soaring gasoline prices also forced designers to pay more attention to aerodynamics than to tail fins and other ornamentation. Now the quest for fuel efficiency has revived interest in an idea that has been around as long as the automobile itself: the continuously variable transmission, or CVT. Such a transmission—operating without gears—promises to boost fuel economy by as much as 30% over that of standard automatic transmissions. Controlling the ratio between the engine and the power train continuously, rather than in steps as with gear-type transmissions, lets an auto engine always operate at its most fuel-efficient speed, even over widely varying load conditions. Usually this is done with belts and pulleys, but other CVT schemes are also being investigated.

The world's automakers, in fact, are now in a race to bring CVT cars to market. Ford, which is tooling up its plant in Bordeaux, France, for CVT production, and Fiat are both ready to introduce such a car to the European market this summer. General Motors is pumping $180 million into its Hydra-matic plant in Strasbourg, France, to build CVTs. Subaru recently announced plans for a similar move in Japan. Volvo has undertaken limited production of CVT cars since 1974, when it acquired a major share in a Dutch company that had been building a CVT car since 1959, the old Daf, or Daffodil.

Once the automakers move into these overseas markets, the next target will be the U.S. In fact, both GM and Ford are talking about introducing CVT cars in this country around '86 or '87, but the race to be first may push that date to next year. Ironically, a continuously variable transmission similar to the one now being adopted was invented by an American, H. G. Spaulding, in 1896. Such a transmission even enjoyed some popularity early in this century, in a car built by the Reeves Company. Eventually, however, the CVT was replaced in automobiles when more reliable and durable geared transmissions were developed. But while the continuously variable transmission faded from the automotive scene, it was soon adopted elsewhere. Today, most snowmobiles, many lawnmowers, and a few motorcycles operate with CVT drives. Over 100 U.S. companies market CVT drives for industrial applications—an indication of their broad appeal.

Though the European Daf was often derisively called "the car that ran on rubber bands," many feel that the CVT will be the transmission of the future, eventually replacing fixed-gear automatic transmissions in small front-wheel-drive cars. Besides providing better fuel economy, it is both lighter and potentially less costly to manufacture than a standard three-speed automatic transmission, because it contains about a third fewer parts. Volvo's sales of more than 20,000 CVT cars last year is proof that this technology is no pipedream.



Fiat's Uno-matic 70 sports a Van Doorne CVT with a metal belt. The steel belt, composed of 320 wedge-shaped steel blocks that move freely along two flexible metal strips, runs between two expanding pulleys that continuously vary the speed ratio of the transmission. The steel belt transmits force by thrust (compression), not tension, and thus provides much greater torque capacity than a rubber belt. As clamping force is applied by the two pulleys, the steel blocks are wedged radially outward to tense the belt. Blocks on the forward run are in compression and transmit engine torque.

Still, not all of the questions on the CVT have yet been answered. Rubber companies are looking for tough elastomers to improve belt durability, and designers are working on beltless drive schemes that would handle more power and would eliminate belt replacement altogether. And the automakers are still looking for better control schemes to fully exploit the CVT's fuel economy and performance advantages. For example, putting the CVT under microprocessor control allows the most suitable ratio to be selected for road conditions, load, and driving behavior. Wider gear ratios will also improve fuel economy, particularly on the open road, where high ratios can keep engine speed low. The spread ratio of the new Fiat Uno-matic 70 is 5.55:1, versus 3:1 to 4:1 in present automatic transmissions. Increasing the CVT's overall speed ratio to, say, 7:1 would easily yield a fuel economy advantage of better than 30% over a standard automatic transmission. It may be possible to go beyond that; a Japanese automaker is funding research at the Univ. of Wisconsin on a CVT that operates with a spread ratio of 10:1.

Continuously variable transmissions appear to be in about the same stage of development as automatic transmissions when they first appeared on the automotive scene.

"CVTs are still in the production tryout phase; the automakers haven't yet tooled up for them in any real volume," points out John Ivey, vice-president for engineering at Borg-Warner's trans-

portation components group (Ithaca, N.Y.). The future will undoubtedly bring many advances, but it is too early to predict how far the improvements will go in practical automotive drives.

Many different CVT schemes have been proposed for automotive use, from the belt-and-pulley setup developed by Van Doorne in Holland to traction drives and pure hydraulic systems. The only serious contender at the moment appears to be the Van Doorne metal-belt transmission, favored by Ford and Fiat, or some close variation, such as the rubber-belt CVT used by Volvo. This has seen the most road experience to date. Volkswagen is studying another type of metal-belt CVT. In the '70s the Dept. of Energy funded research on a hydromechanical drive known as an Orshansky transmission. But, among other drawbacks, this hybrid drive is extremely noisy. DOE funding ceased in '77, and now interest in the Orshansky drive is confined mainly to off-road and military vehicles, reports Bill Weseloh, project engineer of BKM-Orshansky (El Segundo, Cal.).

Although traction drives, which transmit power from one rolling element to another, have been around for nearly half a century, they have made little headway in the automotive market. Several early automobiles—such as the Sears Motor Buggy and the Orient Buckboard—employed traction drives. During the '30s a toroidal (doughnut-shaped) traction drive was offered as an optional transmission by Austin. And in the early '40s, GM seriously considered traction drives, to the point of ordering production tooling, but then backed off. While improved bearing steels and lubricants have overcome many of the problems that have plagued traction drives over the years (low durability, limited power capability), the automakers' interest in these drives at the moment appears minimal.

Yet if the Van Doorne transmission gains a strong foothold, some automaker might reconsider one of these other types of CVT. An interesting variation on the ring-and-cone traction drive, developed by Vadetec (Troy, Mich.) in the '70s, has elicited some interest from the automakers (see "Beltless CVTs: future contenders?").

Unlike the conventional gearbox, a CVT drive allows an engine to operate at its optimal fuel consumption point. The conventional transmission provides only a few discrete gear ratios between the normal "low" and " high" gear—three or four in an automatic transmission and up to five in a manual. In contrast, a CVT drive proceeds in a continuous, or stepless, fashion between the fixed high and low ratios. In a conventional transmission the speed ratio cannot be varied independently of transmitted torque, either because of the fixed gear ratios in a manual transmission or because of the operating characteristics of the torque converter in an automatic transmission. With a CVT, however, the speed ratio can be selected independently of torque, allowing more efficient operation.

Whenever a fixed-gear transmission is shifted, there is a momentary drop in engine speed and a loss of performance; in a CVT, engine speed remains fairly constant, even as the car accelerates. A new driver of a CVT car will notice that engine speed does not increase as the car speed increases, as with a normal gear transmission, and that shifting of a CVT is extremely smooth. When climbing up a steep hill, moreover, there will be none of the shifting back and forth that occurs in a fixed-gear automatic transmission as the power train hunts for the proper gear ratio; the CVT picks the right gear ratio and stays there.

Belt and pulley. Automatic shifting is usually achieved in a CVT with a belt moving around a pair of variable-diameter pulleys, both split longitudinally, with one fixed and one moving half. As soon as one of the split pulleys moves apart, allowing the belt to ride further down in the "V" formed between the two halves, the other split pulley comes together, forcing the belt to ride higher in its groove. In effect, each pulley is always changing in size, one moment acting as a larger gear, the next as a smaller one. The pulleys open and close under command from either a pneumatic (Volvo) or a hydraulic (Ford and Fiat) control unit.

Here is a brief sketch of CVT operation in Fiat's Uno-matic 70: As the car starts, the drive pulley around which the belt winds is at its smallest diameter, so that the CVT works on a low ratio. Acceleration increases belt-wind diameter and gradually closes the drive pulley. At the same time, the driven pulley opens, gradually raising the transmission ratio to the corresponding high-ratio value. The two pulleys are opened and closed by a hydraulic control unit fed by an engine-driven gear pump. The control unit, governed by the instantaneous transmission ratio, accelerator pedal position, and engine rpm, regulates and modulates the pressure on the mobile half pulleys. In particular, the hydraulic valves vary belt compression by the pulleys in response to variations in the drive torque ratio. Belt compression increases as the ratio drops and/or torque increases. At low engine power (light throttle), the transmission quickly reaches high ratios to maintain optimal fuel economy. Flooring the gas pedal will give maximum performance (pick up and acceleration) since the engine reaches its highest speed at the lowest possible ratios.

A rubber belt transmits power in the Volvo CVT, while Ford, Fiat, and GM have opted for the steel-belt Van Doorne drive. The principle of operation is the same, except that the rubber belt works under tension while the steel one works under compression. There are pros and cons for either setup.

Durability remains the biggest problem for rubber belts. Those used in the early Daf cars rarely lasted more than 10,000 miles. However, lifetimes have at least tripled since then; automakers have set a goal of 80,000 miles as the minimum acceptable belt life. In fact, developing a tough CVT V-belt is a top-priority research project for the major rubber companies.

The rubber belt is subject to cyclical forces, such as tight and slack side tension and bending loads, that can lead to fatigue failure. Because excess tension will shorten belt life, it is important that the belt be just taut enough to prevent slippage at each torque load condition. One of the main reasons belt life was so poor in the Daf was the high tension applied on the belt. There's an-

How CVTs stack up against advanced automatic transmissions

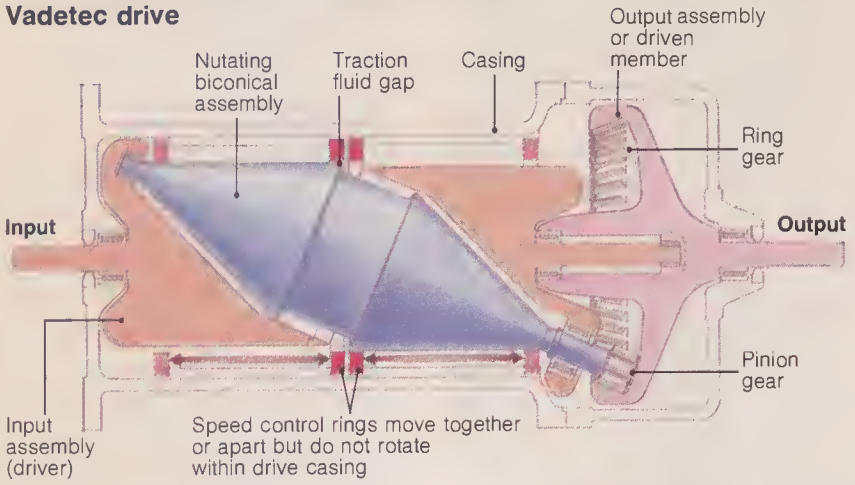
Transmission	Ratio range	Fuel economy improvement, %*		
		Urban cycle	Highway	Composite cycle
3-speed automatic w/lockup	3.0	5–10	5–10	5–10
4-speed automatic	4.0	3–5	15–20	8–11
4-speed automatic w/lockup	4.0	10–15	20–25	14–19
CVT	7.0	18–22	25–30	21–25

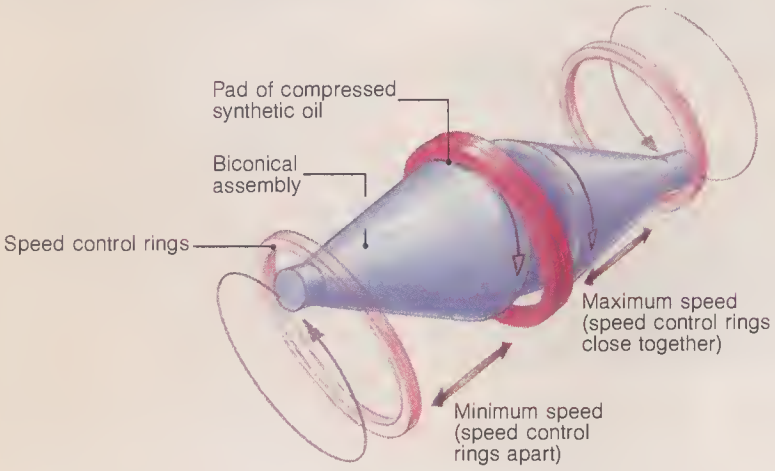
*Over base engine, a 3-speed automatic without lockup torque converter (a type of fluid coupling that prevents slippage) and operating over a ratio spread of 3:1

Source: M. Dowdy and A. Burke. "Automotive technology projections" (SAE paper 790021)

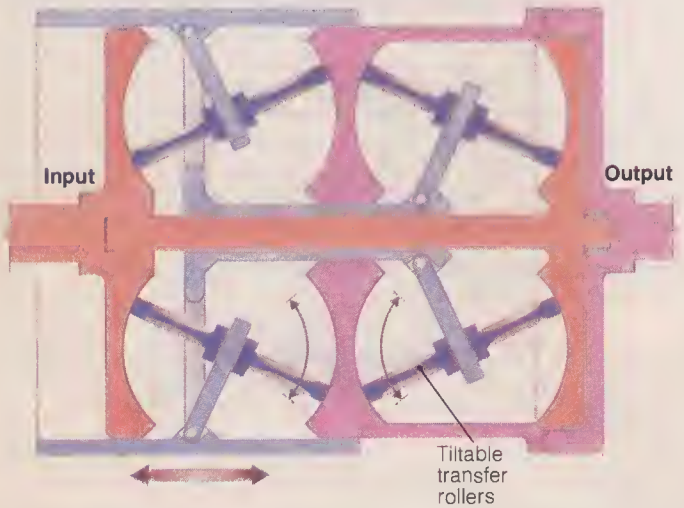
Beltless CVTs: future contenders?

Vadetec drive





Perbury double-cavity toroidal drive



Traction drives. The traction drive has been called the perfect transmission. It is certainly among the simplest, transmitting power from one rolling element to another without gears, belts, or pulleys. Not even a clutch is required, as output speed is infinitely variable down to zero rpm. Early traction drives, however, lacked the power density required for automotive use, and nearly all suffered from the same nagging problem of poor durability as plagued belted CVTs. Traction drives had to await the development of improved bearing steels and synthetic lubricants before they could seriously compete against other types. Development of a lubricant that could resist slippage was the crucial step, since the power output of a traction drive is in direct proportion to the traction coefficient of the lubricant.

Besides possessing a greater traction coefficient than petroleum-based oils, synthetic lubricants (such as Monsanto's Santotrac and Sun Oil's TDF-88) also undergo a remarkable transformation under high stress, forming a glassy film that protects the rolling elements by preventing metal-to-metal contact. Taking advantage of the latest technology, several firms are now attempting to develop traction drives for automotive use. Two of the leading candidates are Vadetec's nutating drive and BL Technology's double toroidal drive.

A variation on the ring-and-cone traction drive, the nutating drive developed in the '70s by Vadetec (a Swiss firm now based in Troy, Mich.) is the essence of simplicity, consisting of only five components (top left). Though quite compact—about a quarter the weight of a belt CVT—the Vadetec drive can handle up to 300 hp, claims company president Yves Kemper. The input assembly is driven by the engine. A double cone mounted within the input assembly at a 20° angle to the horizontal axis wobbles like a poorly thrown football. As it spins around the axis, the centers of both ends of the cone describe circles of equal diameter. This motion is called nutation.

The cone assembly rolls around a set of speed control rings that are free to move axially along the stationary casing. The rate at which the cone assembly spins is determined by its diameter at the point where it touches the rings. Output drive speed is minimal when the rings are spread far apart, and maximal when the rings are close together (middle left). The rings, always searching for the optimal position, are never in the same location for more than a millisecond, says Kemper.

A pinion gear mounted on the end of the nutating cone assembly meshes with the inside face of a ring gear on the output drive shaft. The speed ratio is established by the ratio of the pinion to the ring gear.

Kemper estimates that the Vadetec drive will net a fuel economy gain of

DIAGRAMS BY MARK E. ALSOP

about 20% over a five-speed manual transmission. Manufacturing costs are projected to be approximately two-thirds those of a conventional automatic transmission.

One type of traction drive the automakers are quite familiar with is the Perbury double-cavity toroidal drive. In fact, GM was almost at the point of ordering production tooling for this drive in the early '40s. A similar drive was also demonstrated in a '34 Austin-Hayes and later in a '57 Hillman Minx. But problems with durability (no lubricant could prevent direct roller-to-disc metal contact) and reliability of the drive scuttled further investigations. Until now, that is. BL Technologies (formerly British Leyland), is testing prototypes of the Perbury drive for buses and light trucks.

The double toroidal drive has six tiltable transfer rollers between input and output toroids (bottom of opposite page). A hydraulically controlled linkage system can tilt rollers from one extreme to another. In the past, automakers could never get the hydraulic system to operate properly. BL is reportedly using a microprocessor to control all CVT functions. Prototype drives have shown a gain in fuel economy of about 25% over automatic transmissions.

Hydrostatic drives. A fluid power system differs from a mechanical transmission in that the medium for transmitting power is a hydraulic oil flowing under pressure in a pipe instead of some solid medium—a belt, chain, or gearbox. Yet the two types of transmission have basic similarities. In a simple belt drive, for instance, one pulley drives another via a belt that is kept under tension. In a hydraulic system the driving element is a pump, the driven element a motor, and the power transmission medium—the belt—an oil under pressure in a pipe.

The power transmitted in this fluid system equals the fluid pressure times the flow rate. The pump must be of the positive displacement type, because it must deliver the fluid against a relatively high output pressure. Unlike a torque converter or fluid coupling, a positive displacement pump cannot be stalled.

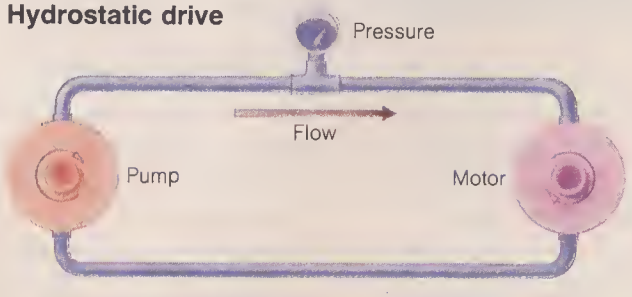
The motor in a fluid power system is very similar in design to a pump, and sometimes the two can be used interchangeably.

Here's how they all work together: (1) the engine shaft—the prime mover—drives the pump, which transfers this energy to the fluid by raising its pressure; (2) the pressurized fluid enters the motor, which transfers energy to the load; and (3) the spent fluid is returned to the pump.

In reality, it's not quite that simple, because a few controls are needed to gain some flexibility. In a fluid power system, three variables can be controlled: direction of the fluid flow, rate of energy transfer, and energy level (pressure). This is accomplished with valves. Directional control valves deliver energy to the right place in the system. A flow valve controls the rate of energy transfer, while a relief valve modulates the pressure level.

Hydrostatic drives have found wide use in the off-road vehicle market, but automakers have shown little interest in them because of their relatively high cost and weight. Furthermore, they are efficient only over a narrow operating range. And they are objectionably noisy for automotive use.

Hydrostatic drive



Belt and pulley drive



other advantage to keeping the belt tension to a minimum. The lower the tension, the faster the shift response to changing load conditions, points out Richard Steig, research engineer at Gates Rubber (Denver, Colo.).

The power capacity of rubber belts has also been restrictive for automotive applications. But, as with belt durability, improvements have been dramatic. The two Goodyear belts operating in tandem in the Daf delivered only 26 hp. Today the twin belts in the Volvo 345 (also supplied by Goodyear) are easily handling 73 hp. The major rubber companies are investing heavily in development of a single belt capable of handling over 50 hp. For example, Gates' Power Trac belt (still under development) has twice the power capacity of a more conventional CVT rubber belt, reports Steig. The belt is constructed of molded rubber trapezoid-shaped blocks fastened to a flat-belt tension member. To further improve the transverse stiffness of the belt, steel reinforcing members are embedded in the blocks.

One way of increasing power capacity is to make the belt wider. The original Goodyear belt was 1.3 inches wide, while the current Volvo belt is around 1¾ inches wide. The Gates Power Trac is 2 inches wide, and Gates is experimenting with still wider ones, up to 3 inches. However, the beltmakers realize that they can't move too far in this direction, because of space constraints in an automobile; making the belt wider means making it thicker. This in turn requires a bigger pulley, since the belt can't bend around as short a radius. The result is a loss of belt efficiency.

Design trade-offs with wider belts are so thorny that better ways are being sought to improve rubber belt drives, according to Andrew Wach, project engineer at Goodyear. The rubber companies are looking for tougher elastomers and more effective reinforcing methods to improve the power density and durability of rubber belts.

The consensus is that these difficulties will restrict rubber-belt CVTs to commuter-type minicars in the one-liter engine class, not a market U.S. automakers want to plunge into at present. Yet despite the drawbacks, rubber belts offer some intrinsic advantages over steel for CVTs. Because a rubber belt running over a metal pulley provides a higher coefficient of friction than steel on steel, the axial loading forces in a rubber-belt CVT transmission are lower. A rubber belt runs dry, while a steel belt must be immersed in an oil bath. A rubber-belt CVT is also lighter and probably less costly to manufacture. Finally, if a rubber belt breaks, it can be replaced easily and cheaply. Volvo's belts cost about $25 each, and a tool is

available that lets the motorist spread the spring-loaded rear pulley halves apart to slip on a new belt.

Van Doorne's belt. Still, the only automaker presently favoring a rubber belt is Volvo. At one time a rubber belt design represented the state of the art in CVTs, so it is not surprising that Volvo chose to go with rubber. Low cost may have swayed Volvo as much as fuel economy, some observers suspect. But the use of metal belts in an experimental car for the year 2000 hints that Volvo too will soon abandon rubber.

Hub Van Doorne, one of the founders of the Daf Company, formed a small engineering firm in the Netherlands in the late '60s to develop a metal-belt CVT. Major capital infusions from the Dutch government, the giant Italian automaker Fiat, and Borg Warner in the U.S. (all of whom acquired shares in the new venture) fueled further research in metal belts. This helped to establish a firm lead for the Van Doorne CVT over competing designs. Twenty "transmatics," representing a second-generation design, were built for Fiat's Ritmos and Strada. During '78 and '79 the Van Doorne transmission accumulated over half a million miles of road testing. And now the first production design is ready for the Fiat Uno-matic 70.

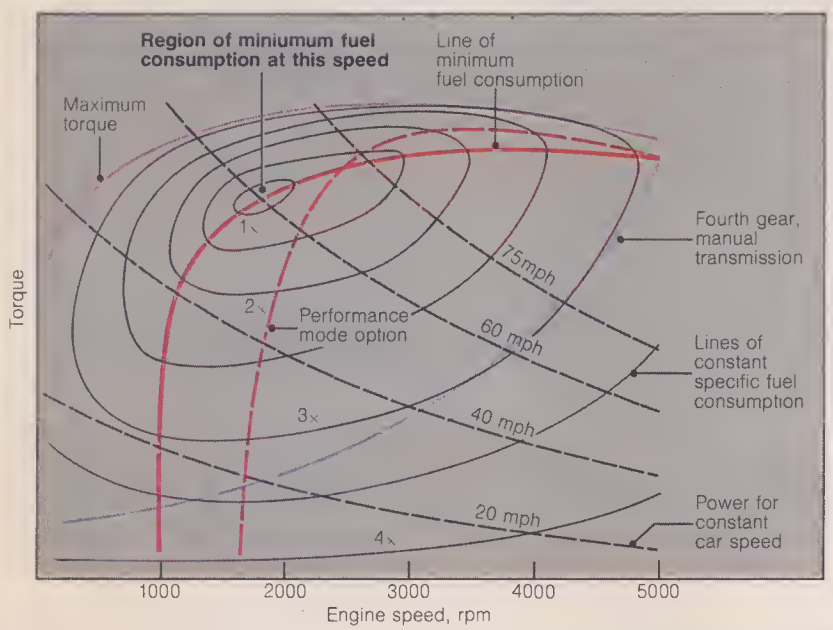
Unlike other belt drives, the Van Doorne CVT transmits power by compression rather than by tension. This gives it much greater torque capacity than other drives of similar size. The belt itself is unique. It consists of a train of 320 thin, wedge-shaped steel blocks aligned and supported by two laminated steel loops. The blocks are free to slide along the loops, much like sliders on a curtain rod. The blocks have tapered edges to match the cone angle of the pulleys they fit into. One face of the steel blocks is gently curved to provide a rocking contact area and uniform load distribution between the curved face and the flat face of the adjacent block. The two flexible steel loops are formed from 10 concentric steel bands, each a little more than a hundredth of a millimeter thick. The bands are of slightly different diameter and are held together by interference fit. The blocks, stamped from steel plate of two different thicknesses, are mixed randomly on the two loops. This eliminates vibration at high speeds. The result is a belt as flexible as rubber.

The design is ingenious, but manufacturing costs are higher than for rubber belts. Thus Fiat is charging about $380 extra for equipping its new Uno with a Van Doorne transmatic.

The efficiency of the transmatic in the Fiat ranges from 88% in low gear to 92% in high gear. That doesn't match the Goodyear rubber belt, which reportedly achieves efficiencies of 96–98%. But it's still much better than a typical automatic transmission with torque converter, with efficiencies of 80–85%. Fiat reports that in fuel consumption the Uno-matic 70 equals an Uno with a five-speed manual transmission.

Rubber-belt CVTs are likely to be restricted to compact cars because of their lower power capability, so metal belts are attractive in spite of their lower efficiency and higher cost. And they do not need replacing.

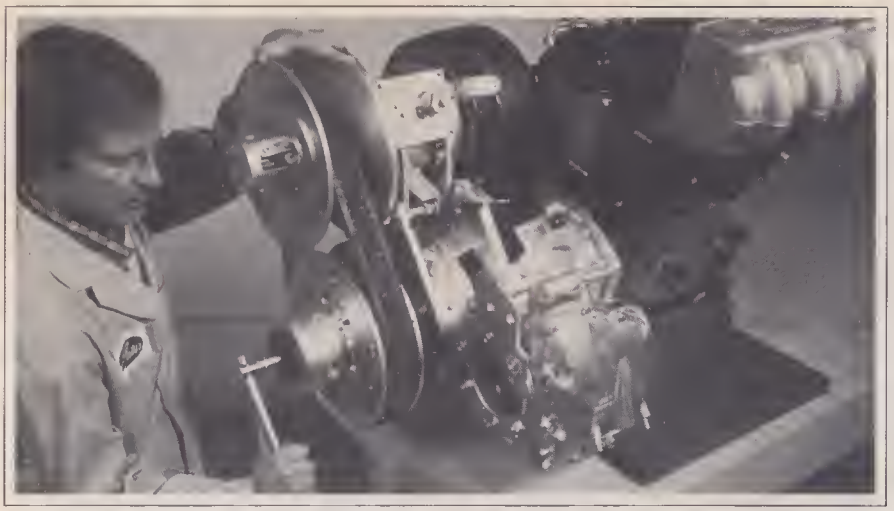
Volkswagen, for example, recently revealed that it is considering another type of metal-belt CVT, developed by the German firm Antrieb Werner Reimers. It's called the positive infinitely variable (PIV) transmission. This is a metal chain drive that, like the rubber-belt drive, rides on pulleys and transmits power through tension. The PIV drive was first tested for automotive applications in the early '60s in BMWs powered by big 6- and 8-cylinder engines. While the PIV demonstrated good durability and efficiency, reports Michael Martin, a project engineer at Aerospace (El Segundo, Cal.), this drive never really caught on in the automotive field. In the off-road market, and in industry, however, the PIV drive has had more success; over a million industrial PIV drives have been sold to date.



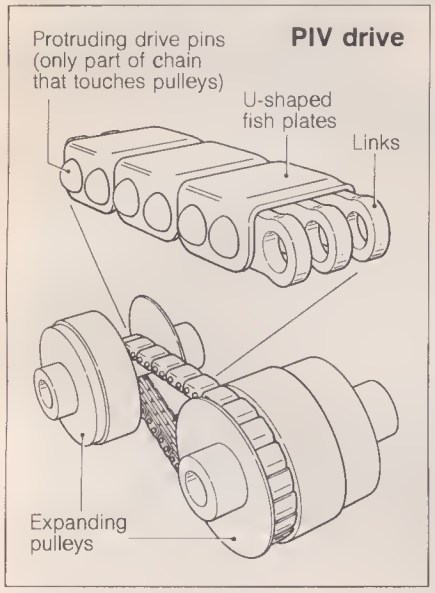
An engine's efficiency can be measured by its specific fuel consumption. This is a typical fuel consumption map for a spark ignition engine. Different combinations of engine speed and load can correspond to the same specific fuel consumption; so if all points of equal specific fuel consumptions are plotted on a graph of engine load versus rpm, the result is a contour map such as this one. Over the full range of engine speeds and loads typically encountered, specific fuel consumption varies greatly. The CVT's advantage is that it allows the engine to operate at its optimal fuel economy point on the map for any power requirement. The locus of these points is an optimal engine operating line, which emphasizes low-speed, high-load engine operation to minimize friction and pumping losses. The electronic control system proposed by Ford allows a driver to choose between best fuel economy and best performance. The performance curve provides maximum engine torque for all throttle positions. The operating points for a four-speed manual transmission are also plotted here. This line is given by the fixed ratio of the fourth gear, which, as the plot shows, misses the most efficient areas of the engine map.

Electronic management. Engineers concerned with fuel efficiency have a good reason to look carefully at transmission technology. The operating characteristics of the conventional internal combustion engine are represented by the classical Otto engine cycle, in which thermal efficiency and hence fuel consumption vary greatly with speed and load.

"Significant gains in fuel economy can be achieved by carefully matching engine operation and vehicle requirements," Martin points out. This gives automakers a number of options for saving fuel. With a manual transmission, which is relatively efficient in terms of power in/power out, fuel econ-



Gates Rubber Co.'s Power-Trac belt (above), constructed of molded rubber trapezoid-shaped blocks reinforced with steel, has twice the power of conventional rubber CVT belts.



In a positive infinitely variable (PIV) chain drive the chain rides in conical pulleys under tension, similar to a rubber-belt drive. Three bicycle-type links are joined by a pair of drive pins fitted through U-shaped fishplates that couple adjacent chain links. Pivoted construction results in an extremely flexible belt that can bend around small radii.

omy can be improved by increasing the number of available gear ratios and widening the ratio spread. There have been a number of similar developments in automatic transmissions (such as lock-up torque converters, which prevent slipping, and added overdrive ratios). Ford reportedly is even working on a six-speed automatic, perhaps as a hedge against poor public acceptance of the CVT. But these developments involve added weight and have thus found only limited use in small cars. Moreover, although these variations on the conventional drive offer incremental improvements, fuel performance can't be fully optimized without some kind of CVT drive.

A CVT allows the engine to operate at its optimal fuel economy points for any given output power requirement (see engine map illustration). This optimal line emphasizes low-speed, high-load operation to minimize friction and pumping losses, and it yields secondary fuel economy benefits as well. For example, the CVT can improve performance by allowing the engine to operate at peak power output during acceleration. Thus a smaller engine can match the performance of a larger engine coupled to a conventional transmission. Fuel economy can be further improved by recalibrating the engine, or redesigning it, to take advantage of the CVT's emphasis on high-torque, low-speed operation.

Many control schemes have been proposed to ensure that the CVT delivers optimal fuel economy. Present systems employ either hydraulic or simple pneumatic controls to activate the start-up clutch, provide adequate clamping forces and belt tension, and control ratio change. The next generation of CVT cars will undoubtedly put some of these functions under microprocessor control to substantially boost efficiency. In the electronic management system proposed by Ford, the engine map stored in microprocessor memory will be used to establish the required hydraulic line pressure to transmit the torque required for a particular engine speed and throttle pedal position.

One of the major advantages of a CVT over a conventional automatic transmission is the possibility of a tailored ratio control strategy to suit the operating characteristics of a specific engine. Because a number of control strategies can be stored in memory in an electronic control system, drivers could select whichever operating mode they wish (i.e., economy or performance).

The electronic control system proposed by Ford receives the following inputs: (1) engine speed, from the ignition coil; (2) car speed, from an inductive sensor installed in the speedometer; (3) throttle angle, from a throttle-position potentiometer; and (4) mode signal, from a dash-mounted switch pressed by the driver. The appropriate ratio control strategy is determined by computer software on the basis of mathematical algorithms making use of data permanently stored in the microprocessor. Present control systems allow only a single operating strategy, based on either economy or performance mode; but an electronic ratio control system could accommodate at least two different options, so that economy and performance would be compromised as little as possible.

Once an optimal engine operating line is selected, the continuously variable transmission in essence controls vehicle performance. This not only allows greater flexibility in vehicle design, says Professor Andrew Frank at the Univ. of Wisconsin's Electrical Engineering Dept., but means that it will be possible to consider engines that in the past were ill suited to automotive use, such as two-cycle engines and gas turbines. The torque curve of the single-shaft gas turbine, for example, decreases sharply from its maximum value at maximum engine speed to zero net output at about half maximum speed. Because of this unusual torque-speed curve, the gas turbine will have to operate over a much narrower speed range than any current automotive engine, says Yves Kemper, president of Vadetec. Thus the transmission used with this engine will require a wider speed range than currently available from conventional stepped transmissions. That means a CVT will probably be needed to make the gas turbine a viable engine for automotive use. □

Ernest Raia is a senior editor of HIGH TECHNOLOGY.

For further information see **BUSINESS OUTLOOK** *on next page and* **RESOURCES** *on page 78.*

BUSINESS OUTLOOK

Gearless transmissions set for debuts

Although they've been around since the turn of the century, continuously variable transmissions (CVTs) have only recently developed to the point of arousing interest among automakers. A 25-year effort by Van Doorne, a Dutch manufacturer, has culminated in a metal-belt and pulley design that is cheaper to build and to operate than conventional automatics.

Volvo, with its European model 345, is now the only manufacturer providing a CVT option. A rubber-belted version of the Van Doorne device was sold in 20,000 Volvos last year.

By 1987, however, as many as 3% of the 10.3 million cars expected to be sold in the U.S. may include CVTs, according to David Cole, director of the University of Michigan's Center for the Study of Automotive Transportation (Ann Arbor). CVT models, he says, should account for 7% of annual automotive sales by 1990, 14% by '92.

Ford, Fiat, and Subaru plan to unveil cars with Van Doorne CVTs by late this summer, followed by GM in mid-1985. Other manufacturers, including Nissan, British Leyland, Renault, and Volkswagen, are developing their own CVT designs. "I don't know of any automaker that isn't involved with CVTs," notes Cole. "We may be witnessing one of the biggest revolutions to hit the auto industry in decades."

Although Van Doorne is now the only source of CVTs, both Ford and GM, under a licensing agreement with the Dutch company, hope to begin assembling the transmissions in France by 1986. Ford has invested $55 million in retooling a plant in Bordeaux, and GM has spent more than $180 million on a plant in Strasbourg.

Even when those facilities are up and running, however, Van Doorne will probably continue supplying the belt and pulley components, according to Richard Curran, president of the transmission group at Borg-Warner (Chicago). He adds that Borg-Warner will serve as a second source. Borg-Warner and Fiat each own 24% of Van Doorne; Volvo Car, the Dutch government-controlled affiliate of Sweden's Volvo, owns the remainder.

The future of CVTs in the U.S. depends largely on their performance over the next two years in overseas markets. Ford, Fiat, and GM are aiming their first CVT models at the European market, Subaru at the Japanese. Automakers do not plan to introduce CVTs in the U.S. until at least 1986.

Although acceptance of the transmissions is expected in Japan, their success in Europe is by no means assured. European drivers, faced with high fuel prices, have traditionally shunned gas-guzzling automatics. Japanese drivers, though, are increasingly turning to automatics to cope with stop-and-go urban traffic. Ninety percent of all new cars purchased in Europe last year had standard transmissions, versus 60% in Japan.

"It's not that Europeans dislike automatics," says Kaywin Goodman, product strategy manager for Ford International (Detroit). "They just don't like spending a lot of money on gasoline." But because CVTs consume as much as 20% less gas than conventional automatics, Goodman contends that they may force Europeans to reevaluate their buying patterns.

By the time CVTs make their U.S. debut, says U. of Michigans's Cole, automakers will have had the chance to test durability, cost, and user acceptance. More important, he adds, they will have determined whether CVTs can be scaled up to operate in larger cars without losses in performance.

CVTs now provide their greatest fuel economies in compact and subcompact cars with engine displacements of less than 1600 cc. While those cars represent a 40% share of the European and Japanese market, they account for a much smaller percentage of U.S. sales. Ford is designing its CVTs for cars with displacements of 1100–1600 cc, but GM is targeting larger models.

If suppliers develop a CVT for mid- to full-size cars, automakers may well find their biggest market for CVTs in the U.S., notes John Schnapp, an automotive industry consultant with Temple Barker and Sloane (Lexington, Mass.): "Americans would embrace any technology that allowed them to have a full-size car with the fuel economies of today's smaller cars."—*F.J.C.*



"Anyone who doubts Ford's commitment to CVTs has only to look at the $120 million we've invested in designing them and retooling our plant in Bordeaux. We'll continue to pursue CVTs through the next decade."

Kaywin Goodman
Product Strategy Manager
Ford International

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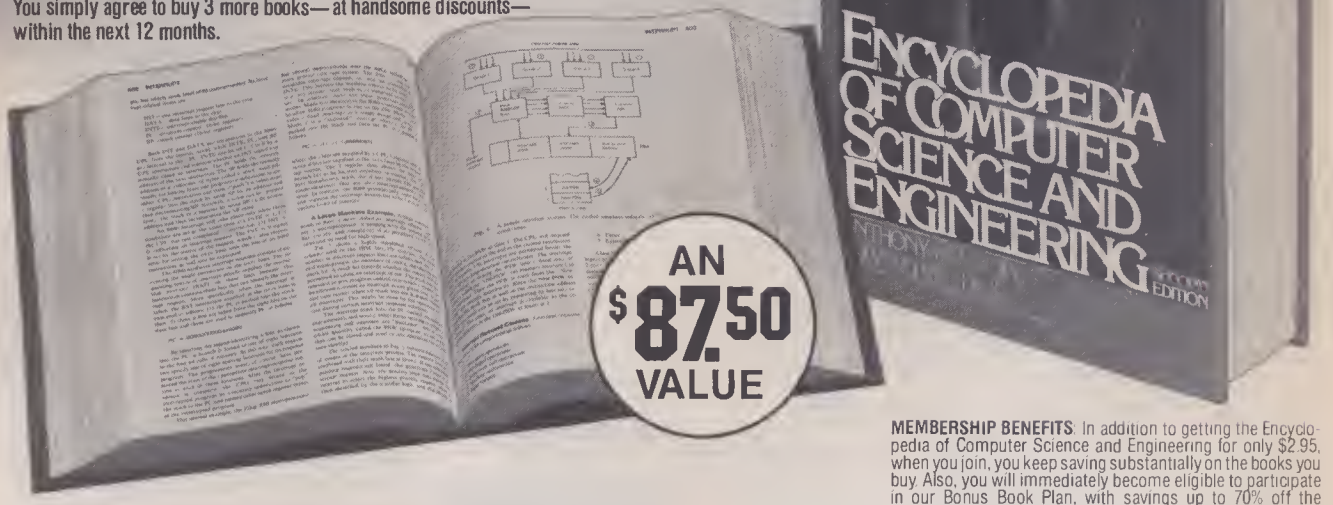
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High Technology 7/84

PERSPECTIVES

High technology export controls

U.S. high technology industries fear that Rep. Don Bonker (D-Wash.) is right when he says that "confusing export procedures may knock us completely out of the global market." These procedures are the subject of a charged debate over how to control commercial products that could have significant military applications. One side argues that boosting U.S. high technology exports helps the U.S. stay ahead of the Soviet Union and that controls only cripple our own technological progress. The other side maintains that denying advanced technology to the Soviets reduces our defense burden, thus aiding our economic strength.

The main argument is over two bills—now stalled in a House-Senate conference committee—to extend the Export Administration Act (EAA). Meanwhile, the Departments of Defense and Commerce are bickering about who should enforce the act. And the U.S. is wrangling with its Western allies over which high technology products to control.

Legislative battles. The original controls on exports expired last September but have been extended—first by Congress, then by President Reagan. The Administration fears that some of the proposed EAA changes would compromise the President's regulatory and foreign policymaking powers. Some of the main conflicts over EAA reauthorization include:

• *Foreign availability.* Shutting off U.S. exports of technology doesn't effectively deny Soviet access if those U.S. products are available from other countries, such as France. EAA now directs the Commerce Secretary to consider lifting controls in cases where technical advisory committees (TACs)—groups of industry and government consultants sponsored by the Dept. of Commerce—say foreign availability exists. The Senate and House bills would require the Secretary to lift controls except where there is evidence to counter the TAC findings. The House also wants to set a time limit for decontrol of 18 months after TAC certifies foreign availability.

• *Decontrol of exports to allies.* Members of the Coordinating Committee for Multilateral Export Controls (CoCom—NATO countries except Iceland and Spain, plus Japan) share a list of controlled products. Despite this cooperation, the U.S. unilaterally controls some goods (more than are on the CoCom list); manufacturers who export goods on the U.S. list must obtain a license for shipment to CoCom countries. Both the Senate and the House want to decontrol all exports to CoCom countries, but the Senate would give the Secretary of Commerce more power to make exceptions.

• *Pentagon review.* There is now a dispute over whether EAA authorizes the Pentagon to review export licenses to noncommunist countries. In March 1984, President Reagan gave the Pentagon this right in cases involving items such as semiconductor-manufacturing equipment, computers, lasers, and certain numerically controlled machines. The Senate is seeking to spell out a DOD role in handling exports to noncommunist countries if strategically sensitive goods could be diverted. The House would leave the law ambiguous.

• *Contract sanctity.* Allowing the President to invalidate existing contracts when the U.S. is embargoing sensitive technology—as President Reagan did in banning sales of oil and gas equipment for the European-Soviet pipeline—makes the U.S. an unreliable supplier, business interests argue. Although the Senate wants to bar such retroactive bans in peacetime, the House bill would give the President several loopholes to invalidate existing contracts.

• *Licensing delays.* Statutory deadlines for issuing export licenses on controlled items vary from 30 to 180 days, depending on their potential military applications and their destination. The Senate bill would reduce licensing time by a third (e.g., from a 30- to a 20-day deadline). The House would reduce deadlines for certain export categories and require that Commerce report to Congress on applications not handled within those deadlines.

• *Enforcement.* The Dept. of Commerce is now the primary enforcer of the EAA. But it has to rely on other agencies, particularly Treasury's Customs Service, for certain actions such as seizing goods at U.S. ports. The Senate would increase Customs' statutory



Special agents of the U.S. Customs Service inspect a VAX 11/782 computer seized in November 1983 in Hamburg. The equipment had been en route to the Soviet Union.



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responsibility; the House would limit it. Some industry officials feel that the Dept. of Commerce is more knowledgeable about its products and easier to deal with than Customs, which has gained a broader role under the Reagan Administration. Customs is now planning Project Rampart, whereby controlled electronic equipment with special chips embedded would trigger sensors at Customs inspection posts in much the same way that tagged goods set off alarms when removed from stores. But critics of the plan point out that the system would not be effective outside the United States without the cooperation of the NATO nations, many of which are already balking at previous U.S. attempts to control electronics equipment.

Commerce vs. Defense. The other area of conflict is within the Administration, chiefly between the Dept. of Commerce and the Pentagon. Commerce officials insist that DOD's license review privilege (as conferred by Reagan and supported by the Senate) will increase delays in processing export license applications.

Commerce hopes to avoid DOD license review by strengthening regulations for so-called distribution licenses (DLs). These blanket licenses exempt some 700 companies that regularly ship to overseas distributors or subsidiaries from having to license each shipment. The department has put forward three major changes. Distribution licenses would be banned for such high technology equipment as semiconductors and lasers. Foreign recipients of U.S. goods would be required to get U.S. permission for each resale or reexportation of those goods to certain countries. And overseas distributors of U.S. goods would have to list all countries in which they have customers and all countries with which their customers trade.

U.S. firms of all sizes will suffer from the proposed rules, claims the Washington-based Industry Coalition on Technology Transfer (including the Aerospace Industries Association and major electronics, computer, and semiconductor groups). The restrictions, asserts the coalition, would send overseas purchasers into the willing arms of foreign competitors and would violate foreign privacy laws. Furthermore, the resulting paperwork would swamp the Commerce Dept., adding to licensing delays.

Controlling exports to allies. The U.S. has been trying for years to update the CoCom restrictions. For example, the Pentagon now proposes that CoCom control all computers 16-bit or larger and give "serious consideration" to U.S. proposals on controlling PCs, telephone switching equipment, and oil and gas exploration and production equipment, says Richard N. Perle, Assistant Secretary of Defense for International Security Policy.

But U.S. efforts to strengthen controls by exerting pressure on our allies are ineffective, claims William A. Root, former U.S. State Dept. representative to CoCom. The deadlock in CoCom has cost the U.S. "lost orders to customers in other Western countries who wish to avoid the uncertainties of our controls on exports and reexports," he says. Furthermore, U.S. unilateral controls that go beyond CoCom's "create a perverse incentive" for U.S. allies to feel "free to soak up Western markets," says Ken Hagerty, vice-president of the American Electronics Association's Government Operations. □

—Dan Gottlieb

Solid-state cameras improve TV's image

As every television viewer knows, conventional TV cameras based on vacuum tubes have some annoying limitations: They produce ghosts that lag behind rapidly moving objects, cometlike streaks that trail after car headlights, lack of detail in dimly lit scenes, and flaring and afterimages when aimed at brilliant light sources. In addition, camera tubes must be replaced, at considerable expense, when they age and burn out.



Split-screen comparison demoustrates that the CCD camera (right) outperforms a conventional tube camera (left) iu dynamic resolution— the ability to show detail in a rapidly moving object.

Because these drawbacks are inherent to vacuum-tube technology, a number of manufacturers have sought to develop solid-state cameras that would yield superior results. Until recently, however, solid-state imaging devices—such as metal-oxide semiconductor (MOS) capacitor arrays and charge-coupled devices (CCDs)—lacked the resolution and dim-light sensitivity required in a broadcast-quality camera.

Now two professional solid-state cameras have been introduced that utilize CCD chips to produce live color TV images with a clarity approaching that of film. These cameras are compact field units designed for electronic newsgathering, sports coverage, and commercial production. The SP-3, distributed by NEC's Broadcast Equipment Div. (Elk Grove Village, Ill.), has a resolution of 525 horizontal lines, weighs 5.9 pounds, and costs about $20,000 without lens. The CCD-1 Color Broadcast Camera, developed by RCA's Broadcast Systems Div. (Gibbsboro, N.J.), is a 13-pound unit that sells for $37,500 without lens. (A typical lens costs $6000.)

The RCA camera is based on a new type of CCD chip called a "frame-transfer" device, which, according to the manufacturer, offers breakthroughs in sensitivity and signal-to-noise ratio. Inside the camera, the image created by the lens is split by a prism into the colors red, blue, and green, which are then focused onto three CCD chips, each less than a half-inch square. Ordinary CCDs offer limited resolution because the imaging areas alternate with masked storage areas over the surface of the chip; in bright scenes, light sneaks under the masks, creating lag. In contrast, the frame-transfer CCD shifts the charge information for each TV frame from the imaging portion of the chip (the image register) to a separate part of the chip (the storage register), where the data are stored for processing.

The image register consists of a 403-horizontal by 512-vertical array of semiconductor elements, each of which generates an electric charge proportionate to the amount of light it receives. During the vertical blanking interval (the black bar between frames), staggered sets of timing voltages applied across the CCD elements transfer the charge packets along par-

RCA

allel channels to the adjacent storage register. The charges are then read out line by line through an output register. Meanwhile, a new charge image is being formed in the image register. (The storage and output registers are optically shielded to prevent stray light from affecting the stored charges.)

The major drawback of camera tubes is the partial retention of previous images, which mix with and blur new images falling on the tube surface. Frame-transfer CCDs obviate this problem by clearing the imaging area of the chip of its electrical charges before it receives new information. As a result, there is no memory of the previous image to create lag; each frame is fully independent of the previous one.

If a scene is well lit and contains little or no motion, the resolution of the CCD camera is virtually identical to that of a good portable tube-camera. But where there is low light or rapid motion, frame-transfer CCDs deliver superior image quality because of their ability to resolve detail in moving objects, a feature known as dynamic resolution. For the first time in live television images, it is possible to distinguish signs on the sides of moving taxis and spokes in a rotating wheel, as well as sharp details when the camera is panned across a scene.

CCD cameras also excel at handling brilliant highlights, such as the glare of the sun off a car window. Tube cameras suffer from "blooming"—a spreading patch of white that lingers after a bright flash—as well as severe and even permanent afterimages. To solve this problem, RCA's new CCD chip incorporates structures called blooming drains, which "perform the same function as storm sewers on city streets," according to Sid Griffin, chief video engineer at RCA. When the number of electrons generated in a pixel area has exceeded the maximum, the blooming drains carry off the excess electrons, preventing them from spilling over into adjacent pixels. As a result, bright highlights are confined to the spot where the light strikes the chip, and the camera recovers immediately from overload, leaving no residual image.

Night scenes photographed with the CCD camera reveal more detail in shadowed areas and reproduce colors well in dim light. "I hesitate to call it a film look, but in a demonstration I saw it certainly did approach that with regard to light levels," says Mark DuPre, managing editor of *Video Pro* magazine. "I was impressed by how the whites didn't flare and the blacks didn't turn to mud." The CCD images also lack comet tails behind car headlights, although a small amount of lag may be visible on a home TV screen because of the afterglow of phosphors in the picture tube.

The main drawback of the CCD camera is a defect called aliasing, caused by the nature of the imaging device. In a tube camera, there is a continuous surface on which the image falls and is scanned by an electron beam. In the CCD camera, however, the image is detected by an array of picture elements, so that between the elements there are discontinuities where light is not detected. With certain types of picture material, such as sharp edges or large numbers of vertical lines, this defect becomes noticeable, giving the TV picture a canvaslike texture.

According to Mark Schubin, a technological consultant to the broadcast industry, this problem will eventually be solved by increasing the resolution of the CCD chip so that it contains enough picture elements to make aliasing undetectable on a standard TV screen. "In the area of computer memory, we've gone in a short time from 8K chips to 256K and now 1 megabit chips," he says. "The same thing will happen to CCD technology."

Indeed, RCA is currently working on higher-resolution frame-transfer CCDs suitable for studio cameras. As volumes increase and manufacturing costs decline, CCD chips may even become inexpensive enough for use in video cameras for the consumer market. The result will be a dramatic improvement in the quality of home video productions. □—*Jonathan B. Tucker*

Students pilot "Space Shuttle"

The marriage of video games and education is one that is often tried and that often fails. But "Space Shuttle: A Journey into Space" is showing that a well-designed video game not only can teach—it has helped junior high students improve their science and reading skills—but can actually make children want to learn.

The game, produced by Activision, challenges players to fly a shuttle mission to repair a satellite that is spinning out of orbit 210 miles above the earth. To do so, they have to pilot the shuttle along the optimal flight path, maneuver into docking position above the satellite, and return to earth with enough fuel for a safe landing.

Playing the game has brought home the physics of space flight to 750 sixth, seventh, and eighth graders in San Jose, California, where Activision sponsored a six-week trial of "Space Shuttle" in science courses. At the end of the unit on space flight, students tested well on physics principles, reports Bruce Compton, a teacher at Steinbeck Middle School, and he credits "Space Shuttle" for part of that success. "Its educational value puts it in a class by itself," he says.



A "Space Shuttle" crew at Steinbeck Middle School in San Jose studies its craft.

BLUMENSAADT/MATRIX

An unexpected benefit was the improvement of reading skills. The game manual doesn't shy away from technical terms and sophisticated vocabulary. Students had to learn the terminology and read carefully to comprehend the detailed instructions. "The kids learned that reading is important," says Compton, "If they couldn't read well, they couldn't play."

And the kids wanted to play—before school, after school, whenever they could get a turn on the Atari 2600s. One reason for their enthusiasm was the game's authenticity. Designer Steve Kitchen, hoping to boost the space program, made the cartridge as much like flying the shuttle as possible. "I wouldn't use the game to train astronauts," says Skip Nunamaker, chief engineer at NASA Ames Research Center (Moffett Field, Cal.). "But it's as realistic as possible within the capability of the computer. I was very impressed with Kitchen's talent and what he produced."

The students, though, have no reservations. "They don't appear to think of it as a game; they act as if they were really flying the Space Shuttle," says Compton.

Players must keep track of time, speed, fuel, and orientation of the shuttle. The complexity of the game forces the three-person teams (modeled after the flight crew of the first shuttle) to cooperate, follow the flight checklist, and plan ahead. Like real astronauts, students have to pass through various levels of training before flying a mission. In Level 1, the Autosimulator, the computer "flies" a brief mission, and the pilot uses none of the console controls. All the pilot has to do is land the shuttle. Level 2 gives the astronaut a chance to log practice flights with little risk. Because fuel use is not recorded, there is no restriction on playing time. On-board computers fill in the gaps in the junior pilot's flying skills; most aborts that would end the game are overridden, but the flight indicator shows when errors are made.

When students are ready to test themselves on a no-holds-barred shuttle mission, they can advance to Level 3, where they are in complete control. They soon learn that in space there is no forgiveness; if they make a mistake—such as failing to fire the engines at a precise moment, losing track of the satellite, or using too much fuel in docking—all their work is wiped out. "One group of three kids got all the way through a Level 3 flight," says Compton, "but they forgot to put down their landing gear. After doing everything correctly for 30 minutes, their mission was aborted because of one mistake. To a 14-year-old, that's devastating, but they immediately restarted the game and went through the mission successfully." By the end of the unit, some 20 of 60 students in Compton's class had successfully completed a Level 3 flight.

About 60 of San Jose's skilled "pilots" recently visited NASA Ames Research Center to get a closer look at the space program. In fact, Chief Engineer Nunamaker reports that the students' curiosity and excitement about space appears to be the game's greatest payoff. "The game makes them feel like they're becoming part of the space program," he says. "Before this experience, kids looked on NASA people as special; playing the game makes them feel like they themselves might be able to do this some day." □—*Margie Ploch*

RESOURCES

Following are sources for further information about topics covered in the feature articles in this issue.

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Contact

United States Olympic Committee, Sports Medicine Div., Dept. of Biomechanics and Computer Services, 1750 E. Boulder St., Colorado Springs, CO 80909.

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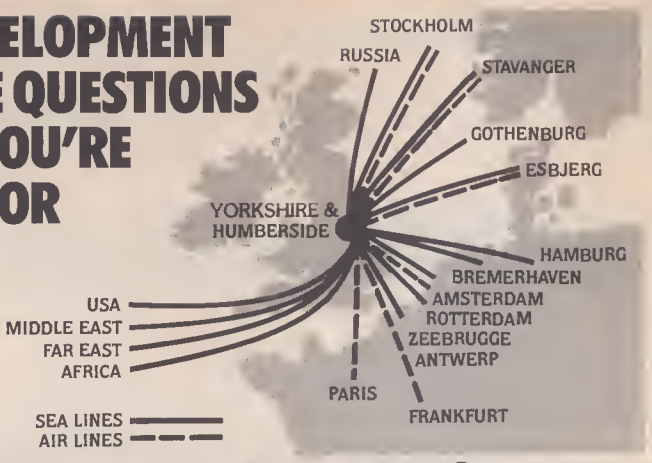
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OPPORTUNITIES ABOUND IN MEMBRANE MARKET

New products trigger market expansion

Used for more than 20 years to desalinate sea and brackish water, membrane technology is now finding a wealth of new applications ranging from concentrating orange juice and milk to controlling the release of drugs that prevent heart attacks and motion sickness.

Although the membrane market has experienced steady growth since its inception, new products and resultant new applications have finally expanded it to a size that is attracting the attention of the investment community. A wealth of venture capital is being poured into the multitude of small privately held membrane vendors, many of which are either gearing up to go public or being acquired by larger corporations. Companies already or soon to be public should be of particular interest to investors.

The U.S. membrane market, growing at an 18% annual rate, was worth more than $327 million last year—a third of the international market. Within 10 years, domestic sales are projected to exceed $1.8 billion, according to a report by Business Communications Co. (Stamford, Conn.).

Separation membranes—used in such applications as desalination, waste treatment, and enhanced oil recovery—accounted for 58% of last year's sales. Newer support membranes (which contain, or "support," substances to be released) accounted for the remainder. These are used primarily in drug release and as catalysts in biochemical reactions. Separation sales, increasing 13.7% annually, will be worth as much as $690 million by 1993; support sales, growing at a 23% annual rate, should exceed $1 billion.

Those revenue projections have prompted large diversified multinational corporations such as Dow (Midland, Mich.), Monsanto (St. Louis), and DuPont (Wilmington, Del.) to participate in the market. Their membrane sales are not a criterion for investment, however, since they account for only a small percentage of the companies' total earnings.

by Anna W. Crull

Among the more attractive private companies that may soon go public are Bend Research (Bend, Ore.), Envirogenics (El Monte, Cal.), and Desalination Systems (Escondido, Cal.). Bend is a technological innovator in both separation and support market segments but is currently focusing its attention on drug-release products. Envirogenics and Desalination Systems are leaders in water purification and waste treatment applications.

Three public suppliers that are of more immediate interest to investors are FilmTec (OTC; Minneapolis), Alza (PSE; Palo Alto, Cal.), and Pall (NYSE; Glen Cove, N.Y.). Each has established products on the market but is positioned to expand its customer base (and annual earnings) through new product development.

Founded in 1977, **FilmTec** is transforming itself from a specialty supplier to a company with a broad product line. The firm is a leading manufacturer of reverse osmosis (RO) separation membranes, which remove particles as small as 1 angstrom and are used mainly in water treatment and purification. But the company is developing new hybrid membranes that incorporate both RO and ultrafiltration technologies (UF removes particles no smaller than 10 angstroms). These new products, especially suited to removing salt from protein and sugar, may find applications in the food-processing industry. The company spent $312,000 on R&D last year and expects to double that figure this year.

In the fiscal year ending November 30, 1983, FilmTec doubled its '82 sales volume and tripled net income and earnings per share. The company netted $918,000, or 38¢ per share, on sales worth more than $5.4 million.

Alza centers its business on drug-release support products and lists such pharmaceutical suppliers as Merck, Baxter Travenol, and Boehringer Ingelheim as its major customers. The company's Transderm-Nitro membrane, marketed by Ciba-Geigy (Ardsley, N.Y.), releases nitroglycerin through the skin (to control the pain of angina) and is the top selling membrane of its kind. Alza has also developed the Alzamer bioerodible membrane, which is expected to find wide use as a means of administering drugs to victims of burns and skin disorders.

The company expects to unveil more than 25 new support membranes over the next two years. Compared with available drug release membranes, Alza's new products will be unique in that they are being designed to support larger than normal drug doses and to release them over extended time periods. Alza is supporting its research efforts with contributions of more than $12 million per year from undisclosed potential customers.

Last year Alza posted revenues of $22.5 million, net income of $1.3 million, and earnings per share of 11¢. In '82 Alza posted revenues of $26 million, net income of $6.5 million, and earnings per share of 46¢. By contrast, the company showed a net income loss in '81 of $6.5 million, or 84¢ per share.

A pioneer in the membrane market, **Pall** was founded in 1946 and has maintained a strong position in the separation market segment. The company's products, based on microporous membrane technology, remove particles ranging in size from 0.04 to 40 microns and are used primarily to sterilize medical fluids. But while fluid-processing products accounted for the major share of Pall's 1983 sales, the company is expanding its business to include membranes for the genetic engineering industry. These could potentially facilitate the transfer of DNA and RNA segments between cells, a process that genetic engineers now find tedious and time-consuming.

Pall's net income for fiscal '83 (ended July 30) was $28 million, or $1.55 per share, on sales worth $215 million. In '82 the company posted sales of $195 million, net income of $25 million, and earnings per share of $1.39. □

Anna W. Crull is president of Chemical Technology Consultants (Houston) and managing editor of the monthly newsletter Membrane/Separation Technology News.

Pharmaceutical climb continues

Pharmaceuticals continued to lead the High Technology Stock Index in April for the second consecutive month, increasing 5.65% over March. The strong showing is attributed to bullish '83 earnings reports issued by individual suppliers as well as to an overall increase in the involvement of companies in the generic drug field. Some of the best individual performers included Bolar Pharmaceuticals (26⅛ to 30), Milan Labs (17¾ to 21⅝), Zenith Labs (16 to 17¼), and Parapharmaceuticals (10¾ to 11¼). Key Pharmaceutical was the only company within the category to lose points. Its stock dropped 2% as a result of a controversy over the effectiveness of a time-release nitroglycerin patch developed for angina patients.

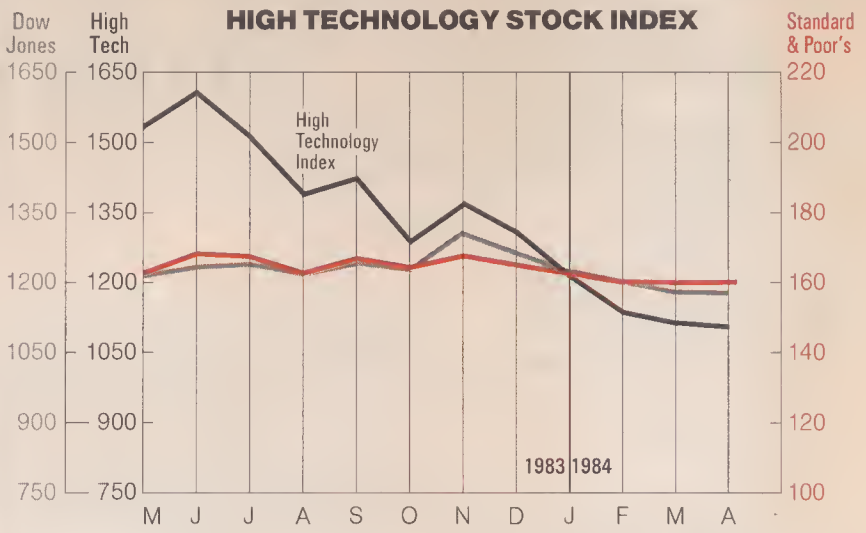
CATV equipment logged the worst performance in the index, falling a sharp 9.65%. Installations have been slowing over the past few months as a result of maturation in the market as well as the looming threat of such competing technologies as videotex, fiber optics, and satellite communications. The hardest-hit companies in the category included General Instruments (24⅜ to 20⅜), C-Cor (10 to 8⅜), and Pico (10⅛ to 8½).

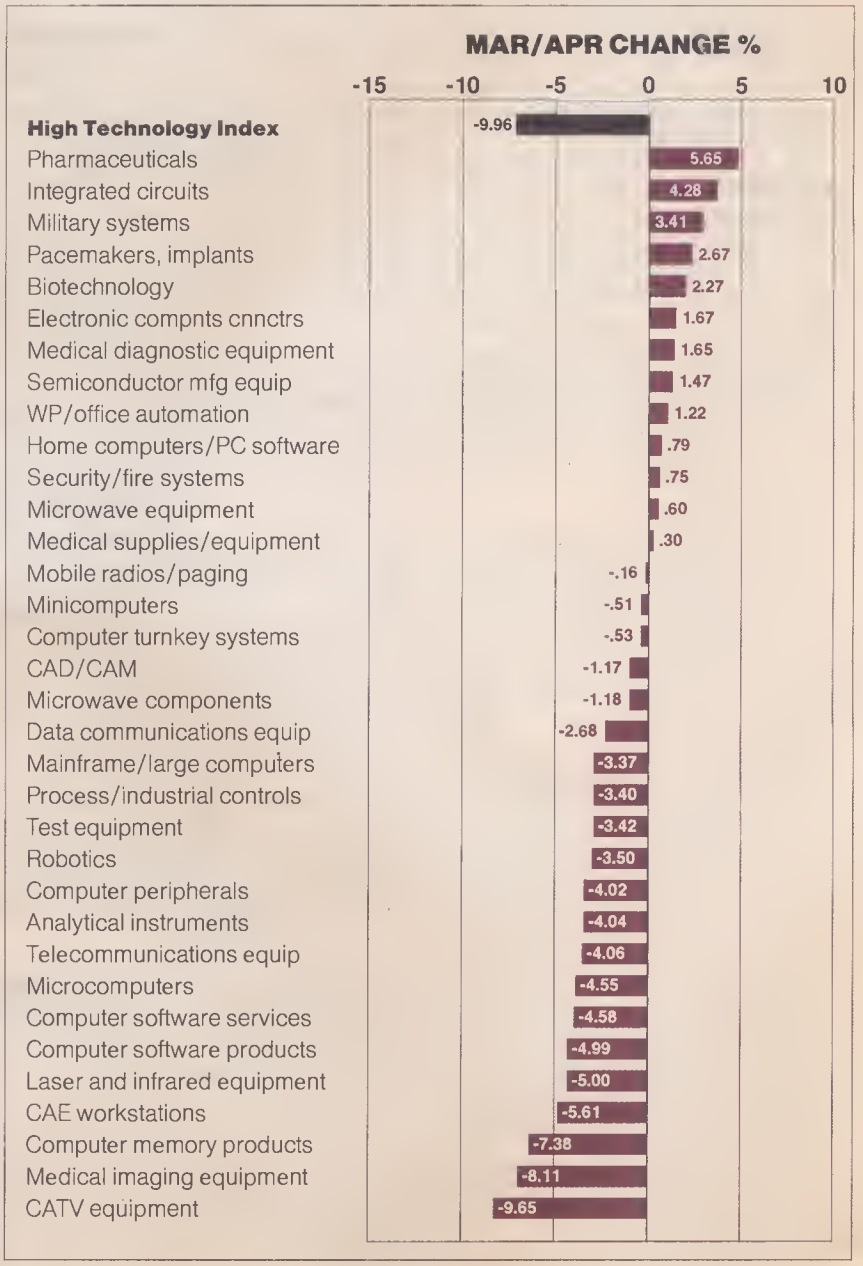
Declines suffered by high technology stocks through March reflected both institutional and private investors' skeptical outlook on the economy. The huge federal deficit as well as slowly rising interest rates resulted in a discounting in the value of traditionally volatile issues.

In April, however, the High Technology Stock Index dropped less than 1%, indicating that the market may have bottomed out. Both the S&P 500 and the Dow Jones Industrials also remained stable.

Institutions began reinvesting in selected high tech stocks whose price/earnings ratios were at their lowest levels in over a year. Private investors, however, remained wary. Their confidence will probably not return until they see some steps taken by either Congress or the Federal Reserve to improve the economic outlook. The slightest change in the economy could cause a sharp upturn in the value of high technology stocks.

The High Technology Stock Index was developed by Bud Anderson, editor and publisher of *High Technology Growth Stocks*, a monthly investment newsletter (402 Border Rd., Concord, MA 01742). A list of companies in the index is available upon request. □





GM

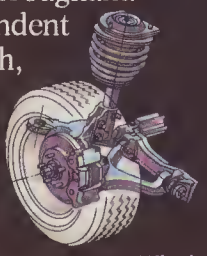
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A spirited new 3.8 liter multi-port fuel injected engine is standard on Brougham models.



Four-Wheel Independent Suspension



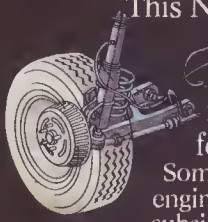
3.8L Multi-Port Fuel Injected Engine

A fuel metering system precisely regulates fuel for optimum performance. An optional electronic instrument panel for precise read-outs is available after June, 1984. Even a voice information system and auto calculator can be added to give you additional assists while driving. An electronic load leveler automatically keeps your Ninety-Eight level, with varying passenger or trunk loads.



Electronic Instrument Panel

This Ninety-Eight also features a new 3-year/36,000-mile, limited new-car warranty. A deductible may apply. See your dealer for details and a test drive.



Electronic Load Leveler

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